



STATIC LOAD CAPACITY ASSESSMENTS OF PORTLAND CEMENT AND METAKAOLIN GEOPOLYMER PRESTRESSED CONCRETE MODEL RAIL SLEEPERS

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ABSTRACT

The determination of flexural load bearing capacity of sleepers under static loading condition is mandatory for prestressed concrete sleepers. This study presents the experimental work on the static load testing requirements of concrete sleepers according to standard EN 13230 – 2 (2009) for both Portland cement concrete (PCC) and metakaolin – based geopolymer concrete (MGC). Tensile strength test was conducted on the prestressing strands and static load test was conducted on the prestressed sleepers to obtain their resistance to flexural load at rail seat and centre sections under normal and inverted positions. The comparative analysis of the estimated and experimental results showed that concrete sleepers of both materials fulfilled the acceptance criterion specified in the said standard. It was found that MGC sleepers exhibited higher safety coefficient under positive loading at centre section by 21%, negative loading at centre section by 13% and negative loading at rail seat section by 18.6%, however, for positive loading at rail seat section the PCC recorded higher safety coefficient by 4%. It was concluded that MGC sleeper generally exhibit higher flexural capacity than PCC sleepers and the implication of this is the allowance for increased locomotive axle load or rationalized cross section of MGC sleepers without necessarily jeopardizing its acceptance requirements.

Keywords: Prestressed concrete sleeper, flexural capacity, metakaolin – based geopolymer concrete, static load testing

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1. Introduction

A ballasted track system consists of substructure and superstructure. The substructure includes components that are associated with the geotechnical system consisting of formation (subgrade), sub – ballast and ballast. The superstructure includes such element as rails and the sleepers. The design of track system requires consideration of load response behavior of all components of rail track to provide acceptable load response and overall lifetime performance (Esveld, 2001). Sleeper is a major structural element in the railway ballast system which supports and sustain the wheel loads on rails and transfer them as uniformly as possible to the ballast bed. Sleeper preserves track gauge and rail inclination and to provide resistant to electrical, mechanical and weathering condition over a long period of time (Sadeghi and Babae, 2006).

Palomo *et al*, (2007) estimated that over 50% of the global demand for sleepers (around 20 million units per year) are of concrete material. This is due to the performance properties and behaviour of concrete sleeper under service condition. In modern concrete sleeper design, prestressed concrete has become a preferable that of reinforced concrete due to the active and better strengthening of concrete at its tension (weak) zone with the prestressing technology, thereby allowing for concrete of higher strength. Concrete sleepers can be classified as mono – block or bi – block elements. While the bi – block are reinforced concrete elements interconnected by a metallic profile, the mono – block sleepers are of prestressed concrete. Mono – block sleepers resist higher loads than the bi – block sleepers and have high durability, but they are usually more than 400kg mass, and require the use of heavy machinery for installation.

Recent studies in rail transport system are looking into the development of new materials with comparably better properties than conventional sleeper materials. One major effort at improving concrete material for special application like sleepers is the inclusion of supplementary cementitious materials like fly ash, GGBFS and other pozzolans in the mix (Chindaprasirt *et al*, 2007). Prestressed concrete sleepers made from alkali silicate activation of fly ash have been tried at laboratory scale in Japan which meets the national standards of Japan (Uehara, 2010). The pilot scale research program in Spain for the development of fly ash based prestressed steam cured sleepers produced sleepers that were able to meet the requirements of Spanish and European specifications (Palomo *et al*, 2007; Fernandez – Jimenez *et al*, 2009). In the absence of fly ash or blast furnace slag, due to lack of industrial presence in developing countries like Nigeria, it is then important to understand the feasibility and adaptability of locally sourced and processed metakaolin – based geopolymer concrete as prestressed concrete sleeper material. Therefore, this study is aimed at filling this important knowledge gap in the research for alternative and improved material for prestressed concrete sleepers. Certification testing on sleeper involves bending tests on a sleeper in which positive and negative bending tests are first conducted at both rail seats and centre section of the sleeper. EN 13230 – 1 (2009), AREMA (2017), and AS 1085.14 (2019) stipulates that static bending tests requires application of the design moment without the appearance of cracks in the sleeper. The requirement for testing in accordance with EN 13230 (2009) differ radically from that of AREMA (2017) with regard to the number of test sleepers. EN 13230 (2009) calls for the

testing of one section per sleeper while AREMA (2017) allow for testing of more than one section for a single sleeper

2. Methods

2.1 Sleeper of Reduced Scale Model

Oftentimes experimentation is the only reliable method for obtaining certain real – life information about material or structural member. In order to save resources, experimental tests are conducted on a geometrically scaled model, rather than the full – scale prototype. In such cases, the results must be properly scaled using a reliable technique most popularly known as dimensional analysis. Dimensional analysis is essential to design and conduct experiments on structural member with clear geometrical outline.

Theory of similarity of the physical models was applied to scale down the geometry of a prototype sleeper to reduced model size since both the prototype and the model maintained certain parameters in common such as: vertical displacement, specific weight and are loaded within elastic limit (i.e. they both obey Hooke's law). Using these three similarity concepts, the non – dimensionalized equations is provided in equation 1 – 3(Azevedo *et al*,2019).

$$\pi_1 = \frac{F}{EI^2} \quad (1)$$

$$\pi_2 = \frac{\gamma l}{E} \quad (2)$$

$$\pi_3 = \frac{\delta}{l} \quad (3)$$

Where E – Young's Modulus of the material (N/mm²), L – length of the sleeper (mm), γ – Specific weight of the concrete material (N/mm³), and δ – Vertical displacement of sleeper (mm). from equation 1, the relationship between the prototype and the model in terms of applied load, specific weight and displacement is as given in equation 4 – 6. Table 1 shows the scale factors for model sleeper. Table 2 presents the dimension of model sleeper as represented from the geometrical description of a typical sleeper in figure 1.

$$\frac{F_p}{l_p^2} = \frac{F_m}{l_m^2} \quad (4)$$

$$\gamma_p l_p = \gamma_m l_m \quad (5)$$

$$\delta_p l_p = \delta_m l_m \quad (6)$$

Where F_p = force applied in the prototype, F_m = force applied in the reduced model

γ_p = specific weight of the prototype, γ_m = specific weight of the reduced model

δ_p = vertical displacement of the prototype, δ_m = vertical displacement of the reduced model

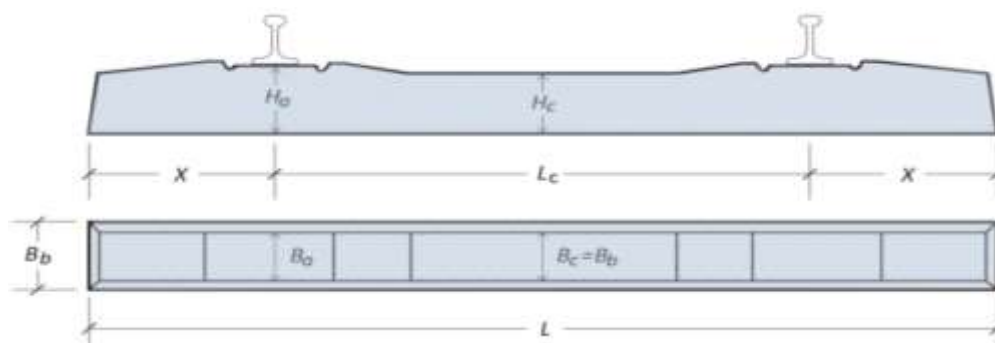
l_p = the length of prototype, l_m = length of reduced model

Table 1: Scale factors for the model sleepers

Parameters	Scale Factor
Applied load	$1:(2.5)^2$
Applied Moment	$1:(2.5)^3$
Specific weight	$1:(2.5)^3$
Vertical displacement	$1:2.5$
Profile area	$1:(2.5)^2$

Table 2: Dimension of concrete sleeper prototype and reduced scaled model

Geometry	Dimensions (Scale Factor 1:2.5)	
	Prototype	Model
Length (L)	2600mm	1040mm
Rail Seat Height (Ha)	214mm	86mm
Mid span Height (Hc)	175mm	70mm
Base Width (Bb)	300mm	120mm
Span (Lc)	1550mm	620mm
Cantilever span (X)	525mm	210mm

**Figure 1: Typical geometry of the sleeper(ABNT, 2015)**

2.2 Preparation of model sleeper for PCC and MGC

The preparation of prestressed model sleepers involved the fixing of strands for pretensioning through the holes in the pretensioning frame and the sleeper moulds. The cables were anchored using anchoring clip at both ends of the frame. Then hydraulic jack was used to move one end of the frame simultaneously as the nuts at the moving end were being tightened to ensure even movement of the plate. The jack load was estimated as 50% capacity of each strand multiplied by the total number of the cables for pretensioning.

After the strands have been tensioned to required stress, concrete was prepared based on designed proportion in Table 3. The fresh concrete was placed in the mould and vibrated using portable vibratory machine. Then the surface of the fresh concrete was finished in the mould before it was covered with polythene sheets until the pretensioned cables were released and the concrete demoulded.

Table 3: Mix compositions for performance properties of PCC and MGC in kg/m³

Concrete type	Portland Cement	Metakaolin	Aggregate		Sodium Silicate	Sodium Hydroxide	Water
			Fine	Coarse			
PCC	715	-	715	715	-	-	255
MGC	-	558	725	725	235	157	-



(a)



(b)



(c)



(d)



(e)



(f)

Figure 2: Prestressing process of PCC and MGC model sleepers (a) prestressing strand (b) tensile test on prestressing strand (c) mould preparation and installation of prestressing strands in mould (d) jacking of the Prestress set up (e) casting of concrete sleepers (f) release of pretensioned strands.

Before the release of prestressed cables, compressive strength test was conducted on cubes prepared from the same mix as the model sleepers to determine the strength attained at the time of release. After the release of the prestressed strands, non – destructive compressive strength was carried out on the sleeper samples using Schmidt hammer to determine the surface strength

of the sleepers. Then the PCC model sleepers were cured in water while the MGC model sleepers were cured in ambient condition for 28 days before the conduct of load test. Figure 2 shows the Prestress process of PCC and MGC model sleepers for this study.

2.3 Prestressed Steel Strands and Sectional Dimensions of the Model Sleepers

The sectional dimension of the model sleeper is as presented in figure 3 (a and b) and the profile of the prestressing strands is presented in figure 3 (c and d). The stress/strain property of the prestressing strands is as presented in figure 4.

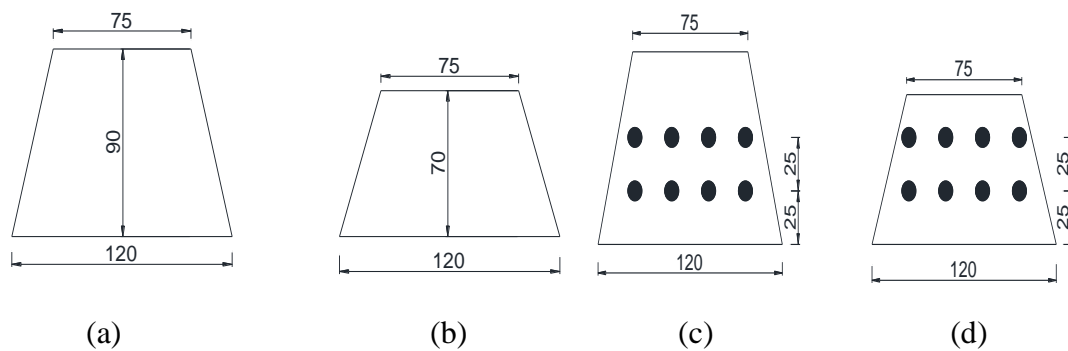


Figure 3: (a) Rail seat section (b) Centre section (c) Profile of strand at Rail seat (d) Profile of strand at centre section

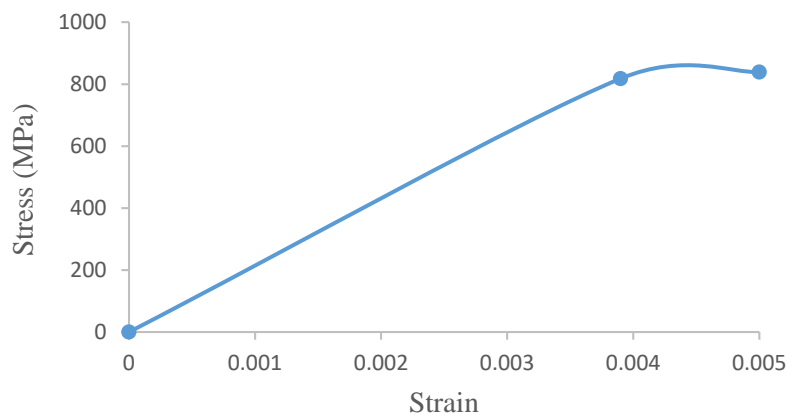


Figure 4: stress/strain curve for PC strands

2.4 Static Load Testing

The static load test was conducted according to EN 13230 – 2 (2009), using universal testing machine in mechanical laboratory at University of Benin. The sleepers were subjected to increasing load at the rail seat and centre section at normal and inverted position until first crack occurred and further of loading until ultimate failure occurred. The test was conducted in accordance with EN 13230 – 2 (2009) and AREMA, (2014). Six sleepers were tested for the

rail seat section to cover both positive and negative loading condition, while three sleepers were tested each for the centre section in normal position and three sleepers for testing in inverted position. Figure 3 presents both the schematic and experimental detail of the static load testing of model sleepers.

The idea behind the static load test is to assess the capacity of the sleeper under flexural loading condition at both rail and centre sections in relation to the initial design force for the sleeper. The initial design force for testing cross section of the sleeper at the rail seat section and centre section was calculated according to EN 13230 – 2 (2009) while the bending moment was calculated according to AS 1085.14 (2019). The results of the initial design force and bending moment are presented in Table 4.

Table 4: Bending moment and test load on model sleeper

Parameter	Equation	Prototype	Model
Rail seat load (R)	$R = \frac{Qj(DF)}{100}$	156.25kN	25kN
Positive moment at rail seat (M_{R+})	$M_{R+} = \frac{R(L - g)}{8}$	21.3kNm	1.36kNm
Negative moment at rail seat (M_{R-})	$M_{R-} = 0.67M_{R+}$	14.3kNm	0.92kNm
Positive moment at centre (M_{C+})	$M_{C+} = 0.05R(L - g)$	8.5kNm	0.54kNm
Negative moment at centre (M_{C-})	$M_{C-} = \frac{R(2g - L)}{4}$	16.4kNm	1.05kNm
Positive reference load at rail seat	$F_{r0} = \frac{4M_{R+}}{L_r - 0.1}$	170.40kN	27.30kN
Negative reference load at rail seat	$F_{ron} = \frac{4M_{R-}}{L_r - 0.1}$	114.40kN	18.30kN
Positive reference load at centre	$F_{c0} = \frac{4M_{C+}}{L_c - 0.1}$	24.10kN	3.90kN
Negative reference load at centre	$F_{con} = \frac{4M_{C-}}{L_c - 0.1}$	46.50kN	7.40kN

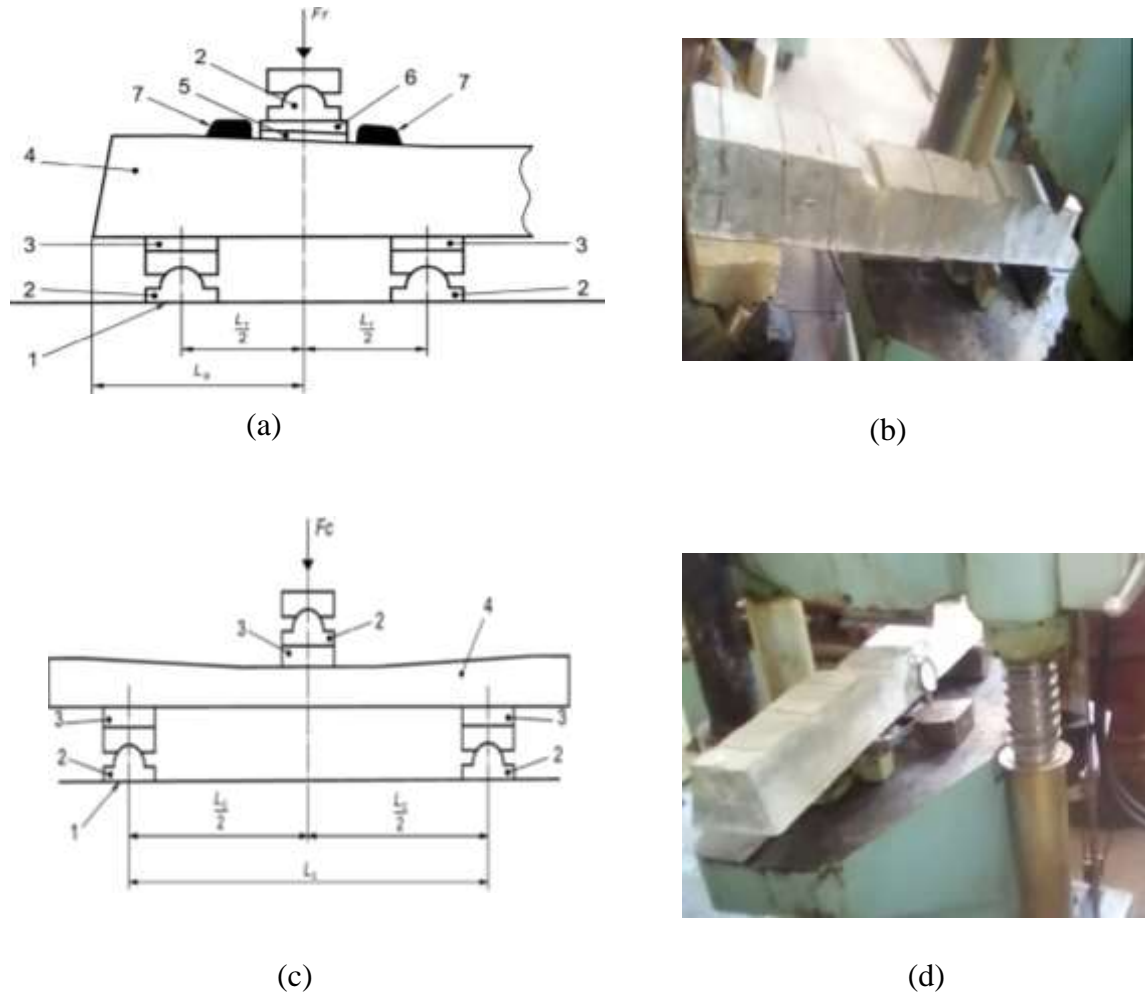


Figure 3: Static load test set up of model sleepers (a) schematic set up for rail seat loading (b) experimental rail seat loading, (c) schematic set up for loading at centre section (d) experimental loading at centre section.

The fulfillment of criteria for acceptance of tested sleepers for a give section is that all test results show that the average values of static coefficient is higher than the minimum allowable safety coefficient. The coefficient of safety is often determined by the purchaser of the sleeper, however, it is based on the standard requirements as contained in EN 13230 – 2 (2009) where it is specified as K_b as presented in table 6, 7, 8 and 9.

3.0 Results and Discussion

The results of the experimental static load testing on model sleepers are presented in table 5 for positive loading on rail seat section, table 6 for negative loading on rail seat section, table 7 for positive loading on centre section and table 8 for negative loading on centre section. A1, B1, C1,...F1 represent model sleepers tested under positive load at rail seat section, A2, B2 and C2 represent the model sleepers tested under positive load at centre section. A3, B3, C3,... F3 represent model sleepers tested under negative load at rail seat section. A4, B4 and C4 represent model sleepers tested under negative load at centre section.

Table 5: Positive loading results at rail seat section

Test force (kN)	Positive load at rail seat section (PCC)						Acceptance Coefficient	
	A1	B1	C1	D1	E1	F1	Average	Minimum
Fr ₀	27.3	27.3	27.3	27.3	27.3	27.3		
Fr _r	37	32	34	35	34	37		
Fr _B	70	73	72	71	74	73		
K _b = Fr _r / Fr ₀	1.35	1.17	1.25	1.28	1.25	1.35	1.28	> 1.0
Positive load at rail seat section (MGC)								
Fr ₀	27.3	27.3	27.3	27.3	27.3	27.3		
Fr _r	32	34	32	35	34	34		
Fr _B	35	38	35	38	36	36		
K _b = Fr _r / Fr ₀	1.17	1.25	1.17	1.28	1.25	1.25	1.23	> 1.0
Fr ₀ = positive initial reference test load for the rail seat section (kN)								
Fr _r = positive test load which produce first crack formation at the bottom of the rail seat section								
Fr _B = positive load at rail seat section at the point of fracture (kN)								

Table 6: Negative loading results at rail seat section

Test force (kN)	Negative load at rail seat section (PCC)						Acceptance coefficient	
	A3	B3	C3	D3	E3	F3	Average	Minimum
Fr _{0n}	18.3	18.3	18.3	18.3	18.3	18.3		
Fr _{rn}	21	25	23	25	24	25		
Fr _{Bn}	24	27	26	26	27	26		
K _b = Fr _{rn} / Fr _{0n}	1.15	1.37	1.26	1.37	1.31	1.37	1.31	>1.0
Negative load at rail seat section (MGC)								
Fr _{0n}	18.3	18.3	18.3	18.3	18.3	18.3		
Fr _{rn}	31	30	29	29	30	28		
Fr _{Bn}	32	33	31	32	32	30		
K _b = Fr _{rn} / Fr _{0n}	1.69	1.64	1.59	1.58	1.64	1.53	1.61	>1.0

Fr_{0n} = negative initial reference test load for the rail seat section (kN)

Fr_{rn} = negative test load producing first crack formation at the bottom of the rail seat section

Fr_{Bn} = negative load at rail seat section at the point of fracture (kN)

From Table 5, it can be observed that both PCC and MGC recorded an average acceptance coefficient that is higher than the required minimum for positive loading at rail seat section of sleepers, albeit marginally. Also there is marginal difference of 4% between the acceptance coefficient of PCC and MGC under this loading condition, and this can be attributed to the reduced scale size of the sleeper under consideration.

From Table 6, it can be seen that both PCC and MGC passes the minimum acceptance criteria for negative loading at rail seat section of sleepers. However, the acceptance coefficient of MGC is a bit higher than that of PCC sleeper which implies that MGC has 19% higher flexural capacity at inverted rail seat section than PCC sleeper before crack.

Table 7: Positive loading results at centre section

Test force (kN)	Positive load at centre section (PCC)			Acceptance coefficient	
	A2	B2	C2	Average	Minimum
F_{C0}	3.9	3.9	3.9		
F_{Cr}	15	14	17		
F_{CB}	22	19	23		
$K_b = F_{Cr} / F_{C0}$	3.85	3.59	4.36	3.90	>1.0
Positive load at centre section (MGC)					
F_{C0}	3.9	3.9	3.9		
F_{Cr}	19	19	20		
F_{CB}	22	21	23		
$K_b = F_{Cr} / F_{C0}$	4.87	4.87	5.13	4.96	>1.0

F_{C0} = positive initial reference test load for the centre section (kN)

F_{Cr} = positive test load which produce first crack formation at the bottom of the centre section

F_{CB} = positive load at centre section at the point of fracture (kN)

Table 8: Negative loading results at centre section

Test force (kN)	Negative load at centre section (PCC)			Acceptance coefficient	
				Average	Minimum
	A4	B4	C4		
F_{c0n}	7.4	7.4	7.4		
F_{crn}	15	13	12		
F_{cBn}	16	15	15		
$K_b = F_{crn} / F_{c0n}$	2.03	1.76	1.62	1.80	>1.0
	Negative load at centre section (MGC)				
	A4	B4	C4		
F_{c0n}	7.4	7.4	7.4		
F_{crn}	15	14	17		
F_{cBn}	15	15	18		
$K_b = F_{crn} / F_{c0n}$	2.03	1.89	2.29	2.07	>1.0

F_{c0n} = negative initial reference test load for the centre section (kN)

F_{crn} = negative test load which produce first crack formation at the bottom of the centre section

F_{cBn} = negative load at centre section at the point of fracture (kN)

Table 7 shows that both PCC and MGC recorded higher acceptance coefficient than the required minimum for positive loading at centre section of sleepers. The higher coefficient of acceptance under this loading condition can be attributed to the flexural support provided by the embedded prestressed strands in the concrete sleepers. However, it can be observed that acceptance coefficient of MGC is higher than that of PCC sleeper which implies that MGC has 21% higher flexural capacity at than PCC sleeper before crack.

From Table 8, it can be seen that both PCC and MGC passes the minimum acceptance criteria for negative loading at centre of sleepers. However, it can be observed that acceptance coefficient of MGC is higher than that of PCC sleeper which implies that the MGC sleeper has 13% higher capacity for flexural load in inverted position at the centre of sleeper than PCC sleepers before the appearance of structural crack.

3.1 Influence of static load on sleepers

The detailed analysis of static test results as per requirements contained in the EN 13230 – 2 (2009) indicates that the tested sleepers fulfill the criteria set for reaching the positive assessment about the quality and load carrying capacity of both the PCC and MGC sleepers.

Table 9 shows the relationship between the estimated and the experimental results of the static loading requirement of the sleepers. In order to convert the results of the reduced model sleepers to their prototype scale the model results would be multiplied by 2.5 for displacement or 2.5^2 for force.

Table 9: Comparative analysis of the estimated and experimental load carrying requirements of sleepers in kN

Reference load and Position	Estimate d	Experiment		Experiment/Estimated ratio	
		PCC	MGC	PCC	MGC
Positive reference load at rail seat	27.3	34.8	33.5	1.27	1.23
Negative reference load at rail seat	18.3	23.8	29.5	1.30	1.61
Positive reference load at centre	3.9	15.3	19.3	3.92	4.95
Negative reference load at centre	7.4	13.3	15.3	1.80	2.07

From Table 9, it can be seen that the both PCC and MGC passes the positive assessment criteria of concrete sleepers since they both exceed the required estimated static load capacity for both positive and negative loading at rail and centre section. However, MGC exhibits a higher flexural load bearing capacity than PCC as indicated by higher safety coefficients obtained in the testing, owing partly to its higher compressive strength and flexural strength than PCC.

4. Conclusion

In this study, the cross section at rail seat and centre section, in normal and inverse positions under static load testing show fulfillment of criteria for positive assessment and acceptance of sleeper as specified in EN 13230 – 2 (2009). However, the MGC sleepers exhibited higher safety coefficient than PCC sleeper when loaded in normal and inverted position at centre section. For the cross section at rail seat in inverted position MGC recorded higher flexural capacity. But the result of the cross section at rail seat in normal position shows that PCC sleeper exhibited marginal increase in flexural capacity than MGC sleepers. In general, it is clear that the higher flexural capacity of MGC sleeper indicates a considerable reserve in the flexural capacity of MGC sleepers, which can be used either for assuming a greater locomotive axle load, or for rationalization of cross section for MGC sleeper.

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