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A New Mix Design Method for Steel Fibre-reinforced, Roller Compacted and Polymer Modified Bonded Concrete Overlays

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Highlights

- A new mix design method for polymer modified, bonded concrete overlays is proposed.
- Main requirements for the mix were: roller compactability and paver placeability.
- Optimal water content was a key element for the roller-compacted, concrete overlay.
- The modified light compaction method (M-L) guarantees high strength and good bond

Abstract

For roller compacted concrete used in pavements, optimal water content is one of main concerns for mix design. However the mix design method aiming at achieving both high bond strength and roller compactability is not available so far. The modified Proctor compaction method and modified Vebe method were investigated and found to be inappropriate to the type of mixes in terms of durability. In this paper a method for determining optimal water content is proposed for steel fibre-reinforced, roller compacted and polymer modified bonded concrete overlays. Two types of mixes suitable for asphalt paver placement and roller compaction were developed: They were the SBR and the SBR–PVA hybrid polymer modified cement concrete mixes with the optimal water contents determined by the proposed method. Both mixes achieved good bond with the old concrete substrate.

Keywords: steel fibre reinforced, roller compacted, polymer modified, bonded concrete overlays

1. Introduction

A vast number of worn concrete pavements used in airfields, highways and urban roads, are rehabilitated every year around the world. The utilisation of bonded concrete overlays (BCOs) can be more sustainable, environmentally friendly and cost effective than the complete removal and replacement of the old concrete pavement. Conventional concrete overlays bonded on old concrete pavements are increasingly gaining acceptance in United States [1–3]. However compared to roller compacted concrete (RCC) pavements, the construction process is slow and unfavourable due to long traffic disruptions.

BCO can offer significant savings, since maximum use is made of the existing structural concrete pavement. However, the overlay has to provide adequate toughness, crack control, high flexural and bond strength and good resistance to fatigue. The constituents and proportion of RCC for pavements have been extensively inves- tigated. The RCC mix designs are mainly focusing on determining the optimal water content. The methods currently available for determining optimal water content are the modified Proctor M-P) compaction method [5,6] and the modified Vebe (M-VB) method [7,8], although they relate exclusively to plain RCC (without steel fibres).

Recently, Kagaya et al. [9] carried out laboratory studies with steel fibre reinforced RCC, using the M-VB method. Neocleous et al. [10] employed the M-P method to develop mixes containing recycled steel fibre reinforced in RCC pavements. However, the abovementioned mix design methods were for pavements resting on a sub-base or a sub-grade but not applicable to bonded concrete overlays. In the present study a good bond between the overlay and the existing concrete pavement is the key to its success. There- fore, it is necessary to develop a new mix design method for steel fibre reinforced, roller compacted bonded overlays. The method proposed in this paper introduces an innovative approach in deter- mining the optimal water content in RCC mixes when used as pavement overlays. Two types of mixes were developed to achieve good bond with existing concrete.

2. Mix Constituents, Workability and Design Criteria

2.1. Mix constituents and their properties

Steel fibres and polymers, such as Styrene Butadiene Rubber (SBR) and Polyvi- nyl Alcohol (PVA), were selected to be included in the mixes to enhance the resistance of pavement to reflective cracking and ensure good bond with the exist- ing concrete substrate. Hence the full name of mixes is ‘steel fibre reinforced, roller- compacted, polymer modified, bonded concrete overlay’. It should be pointed out that the mix constituents of the SBR modified cement concrete used in this study were first considered by Koutselas [11] in an earlier research programme, in which the types of aggregate, glass fibre, SBR, PFA (pulverized fuel ash) and MTK (metaka- olin) were extensively investigated and carefully selected.

The physical properties of materials used are presented in Table 1. The physical properties of cement, SBR, PVA, steel fibre, MTK, PFA and superplasticizer were pro- vided by the suppliers/manufacturers, while coarse aggregate and fine aggregate were tested by the authors in accordance with the relevant British Standards.

The physical properties and chemical compositions of cement, MTK and PFA, provided by the corresponding manufacturers are listed in Tables 2–4. In this study, sand ratio is defined as sand (fine aggregate) to total aggregate (fine aggregate plus coarse aggregate) ratio by weight. The gradations of combined aggregates with sand ratio of 0.345 and 0.4 and 0.5 are presented in Table 5.

Table 1

Materials used and properties

Materials	Properties	Supplier/Manufacturer
Cement	Cement-I, 52.5N, specific density 3150 kg/m3	Hanson Heidelberg Cement Group, UK
Coarse aggregate (CA)	Crushed gritstone, size 4.75 to 10mm, impact value 12.9%, apparent particle density on oven dry 2790kg/m^3, particle density on saturated surface-dried basis 2770kg/m^3, water absorption 0.5%.	Tarmac Ltd, UK
Fine aggregate (FA)	Quartz river sand, apparent particle density 2670kg/m3, fineness modulus 2.476, water absorption 0%.	Coventry Building Supplies, UK
SBR	White liquid, solid ingredient content 46% by weight, water content 54%, specific density 1040kg/m^3.	Everbuild Building Products, UK
PVA	Polyvinyl Alcohol, GH-17S, white powder and water soluble, specific density 1250 kg/m^3.	NIPPON GOHSEI, Japan
Steel fibre (SF)	length 35mm, hooked-end, rectangular section 0.45mm×0.6mm,tensile strength 1050MPa, aspect ratio 60.	Propex Concrete Systems Corp., UK
MTK	Matakaolin, white powder, the specific density 2507kg/m^3, loss on ignition 1% ,water demand (Mars cone) 900g/kg.	AGS MINERAUX, France
PFA	Pulverized Fuel Ash, powder, specific density 2090kg/m^3	Drax Power station, UK
Superplasticizer	Auracast 400, liquid, dark straw, specific density 1020kg/m^3.	Fosroc Ltd, UK

Table 2

Physical properties and chemical composition of Cement-I, of Hanson Heidelberg, UK

Physical property	Chemical compound by weight (%)								
Loss on ignition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Cl
3.30%	20.06	4.42	2.67	64.04	1.19	3.1	0.71	0.21	0.05

Table 3

Physical properties and chemical composition of PFA, of Drax Power Station, UK

Physical Properties		Basic Oxide Composition (average by weight, %)						
Loss on ignition	Fineness	SO_3	CaO	MgO	K_2O	Al_2O_3	Fe_2O_3	SiO_2
4.80%	25.10%	0.77	2.8	1.5	3.1	24.7	8.8	51.2

Table 4

Physical properties and chemical composition of MTK, of MINERAUX, France

Physical Characteristics			Basic Oxide Composition (average by weight, %)					
Loss on ignition	Pozzolanic index (Chapelle test)	Specific area (BET)	TiO_2	CaO+MgO	Na_2O+K_2O	Al_2O_3	Fe_2O_3	SiO_2
1%	1100mg $Ca(OH)_2$/g	17m²/g	1.5	0.3	0.8	40	1.4	55

Table 5

Gradation of combined aggregate

Sand	Cumulative passing by weight (%)									
ratio	14mm	10mm	6.3mm	4.75mm	2.36mm	1.18mm	600μm	300μm	150μm	75μm

0.345	100	95.32	45.21	37.53	30.35	28.28	23.65	3.81	0.98	0.15
0.4	100	95.72	49.82	41.95	35.19	32.78	27.42	4.41	1.14	0.18
0.5	100	96.43	58.18	51.63	43.99	40.98	34.28	5.52	1.42	0.22

2.2. Mix workability and mix design criteria

The focal point of the present RCC mix designs is the determination of the opti- mal water content. In order to simulate conventional concrete overlays on old con- crete pavements in the laboratory, ordinary Portland cement concrete (OPCC) composite cylinders and blocks were first studied. They were fabricated and cured in water prior to testing. Their mechanical properties in 28-day age are listed in Table 6. The OPCC mix proportion in Table 6 was similar to that used in conventional bonded concrete overlays in successful, real pavement sites [4]. Their tensile bond strength was reported equal to 1.65 MPa compared to our splitting tensile bond strength of 2.17 MPa. Thus, the OPCC-to-OPCC bond strengths obtained, were selected to be the lower strength boundary for steel fibre reinforced, roller- compacted bonded concrete overlay.

For RCC bonded overlays in construction, mixes should be dry enough to be placed by asphalt pavers and compacted by vibrating rollers. However, dry mixes may lead to poor bond with existing concrete pavements. On the other hand, good bond could be achieved by using wet mixes due to wet paste sufficiently moistening the interface. However, it may well introduce problems while being placed by pavers due to the mix being ‘lumpy’. Besides, high water content will result in high water to cement ratio and hence low strength. Therefore, the appropriate workability of a RCC bonded overlay mix is defined in terms of ‘‘*roller compactability*’’ and ‘‘*paver placeability*’’, namely a mix with the appropriate workability should be suitable for roller compaction and in the meantime, viable to be placed by asphalt pavers.

For conventional RCC, the mixes with optimal water content determined by the M-P and M-VB method are usually compacted with heavy duty vibratory rollers. However, materials such as soils, with optimum water content determined by the Standard Proctor (S-P) compaction test [5], are usually compacted with light rollers. Too wet mixes may not even be compactable by light rollers. This indicates that the mixes containing optimal water content determined by the S-P method are compactable using currently available rollers.

In addition, in practice concrete used in structural applications should be solid for durability reasons. This means that for RCC in the study, the compacted specimen with optimal water content should have no visible voids.

In general, mixes with appropriate water content for roller compacted bonded concrete overlays should satisfy the following criteria simultaneously: (a) the mix should not become lumpy during mixing and placing; rather, it should behave like a granular material for paver placeability; (b) the water content should not be higher than that determined by the S-P method for roller compactability; (c) the direct shear bond strength and splitting tensile bond strength of PMC-to-OPCC should be at least equal to or greater than that of the OPCC-to-OPCC bond strength (4.09 MPa and 2.17 MPa, respectively); and (d) the compacted specimens with optimal water content should have no visible voids.

Table 6

OPCC proportion and its mechanical properties

Quantities for 1 m³ concrete (kg)				Compressive strength of cube (MPa)	Flexural tensile strength (MPa)	Direct shear strength (MPa)	Splitting tensile strength (MPa)	OPCC-to-OPCC bond strength	
cement	CA	FA	water					direct shear bond strength (MPa)	splitting tensile bond strength (MPa)
402	1116	648	205	60.4	4.66	7	4.57	4.09	2.17

Note: (1) All cubes were: (LxWxH) ≡ (100×100×100) mm. All beams for flexural strength were: (LxWxH) ≡ (100×100×500) mm. Cylinders for direct shear and splitting tensile strengths were: (LxD) ≡ (200×100) mm. (2) Test procedures comply with the relevant British Standard. Test procedures for bond strength are presented in Section 4, in detail.

3. Method for the Determination of Optimal Water Content

In this study, the mixing procedure for SBR modified cement concrete conforms to ASTM C 1439-99 [13]. That is, add coarse aggregate and SBR latex and approximately half the total amount of water; rotate the mixer a few revolutions; add the fine aggregate, cement, and remaining water; mix the concrete for 3 min, followed by 1 min of 'rest', followed by 1 min of further mixing. For hybrid polymer (SBR and PVA) modified cement concrete, the mixing procedure remains the same, except that the cement and PVA are mixed uniformly in a separate mixer, prior to the main mixing procedure. If a superplasticizer is to be used, the procedure will not change, other than the latter being mixed with the water prior to being added in the main mix.

The investigation started by utilising the following methods to explore the appropriate compaction effort: The S-P compaction method [5] (2.5 kg rammer and 300 mm dropping), the M-P compaction method [5] (4.5 kg rammer and 450 mm dropping) and the M-VB method [7] (total weight of 22.7 kg of surcharge and plate). They were experimentally investigated and assessed by the abovementioned criteria. For an accurate validation of the results, the mixes employed in the study were varied in terms of steel fibre content (0–1.5% by volume fraction), SBR to cement ratio (solid ingredient, 3–10% by weight), PVA to cement ratio (0–3% by weight) and dominant coarse aggregate size (10 mm and 14 mm). A modified method was later developed by adjusting the number of rammer drops for each layer, in order to obtain suitable compaction result, and hence the most favourable water content.

The moisture content w, wet density cw, dry density cD and air content a, were used to determine maximum dry density and optimal moisture content in the following section. The relationships used are presented below. The method of ASTM C 138/C138M-01a [14] was used to determine the sample density and air content.

$$w = \frac{W_T - A\times 0.5\%}{C+PFA+MTK+A+S+SBR\times 46\%+PVA+F} \quad (1)$$

$$\gamma_D = \frac{\gamma_w}{1+w} \quad (2)$$

$$W_T = W_a + SBR \times 54\% \quad (3)$$

$$\beta = \frac{\gamma_w}{C+PFA+MTK+A+S+SBR+PVA+Sp+W_a+F} \quad (4)$$

$$V_{a1} = \frac{C_1}{3150} + \frac{PFA_1}{2090} + \frac{MTK_1}{2507} + \frac{A_1 \times 1.005}{2770} + \frac{S_1}{2670} + \frac{SBR_1}{1040} + \frac{PVA_1}{1250} + \frac{Sp_1}{1020} + \frac{W_{a1} - A_1 \times 0.5\%}{1000} + \frac{F_1}{7800} \quad (5)$$

$$a = 100 \times (1 - V_{a1}) \quad (6)$$

Where:

Eqs. (1) - (4): w is the moisture content (%); γ_w is the wet density (kg/m^3) determined by experiments; γ_D the dry density (kg/m^3); W_T the total mass of water (added water plus the water fraction contained in SBR) (kg); W_a is the added water mass (kg); C is mass of cement (kg); PFA is Pulverised fuel ash (kg); MTK is Metakaolin (kg); A is the Coarse aggregate (kg); S is Fine aggregate (kg); SBR is Styrene Butadiene Rubber (kg); PVA is Polyvinyl alcohol (kg), Sp is Super-plasticiser and F is the Steel fibre (kg). Their values are listed in the Tables 7 and 9.

Eqs. (5) -(6): C_1, PFA_1, MTK_1, A_1, S_1, SBR_1, PVA_1, Sp_1 and F_1 are the masses (kg) of cement, Pulverised fuel ash, Metakaolin, coarse aggregate, fine aggregate, Styrene Butadiene Rubber, Polyvinyl alcohol, super-plasticizer and steel fibre in 1 m^3 of concrete, respectively, which are determined by the values listed in Tables 3 and 5 after multiplied by β. Numbers in the denominators of Eq. (5) are densities of the corresponding materials shown. α is the air void content (%); V_{a1} is the total absolute volume of the component ingredients in 1m^3 of concrete.

3.1 M-P method and M-VB method

All mixes employed in the compaction test are listed in Table 7. The quantities of materials in Table 7 should be regarded as proportions, rather than quantities for 1 m^3 concrete. Test procedures of M-P and M-VB methods complied with BS 1377-4:1990[5] and ASTM C 1170-06 [7], respectively.

Table 7
Mixes for various compaction methods

Mix ID	cement	PFA	MTK	CA	FA	SBR	total water	SF
	kg	kg	kg	kg	kg	kg	kg	kg
M1	486	109	40	1053	554	31	variable	0

M2	486	109	40	1053	554	31	39
M3	486	109	40	1053	554	31	117
M4	635	0	0	964	643	138	0
M5	635	0	0	964	643	138	117

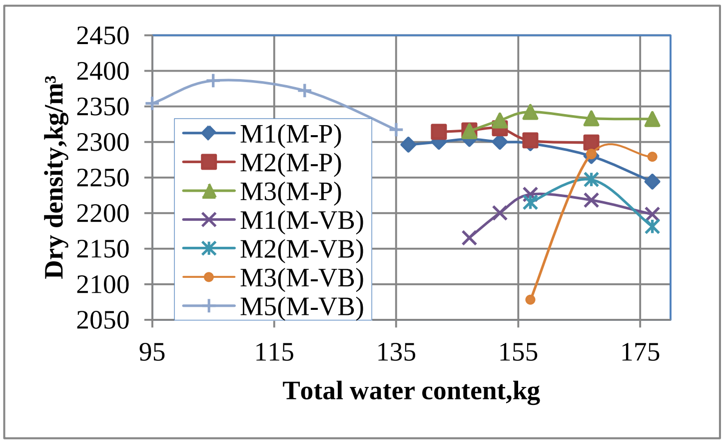

Fig.1 Relationship of dry density and total water by M-P and M-VB methods

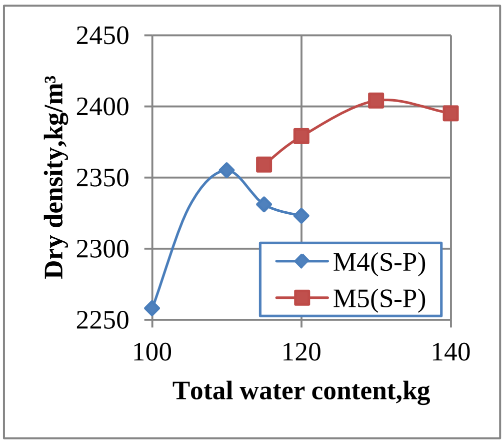

Fig.2 Relationship of dry density and total water content by the S-P method

The relationship between dry density and total water content by the M-P method and the M-VB method is plotted in Fig. 1. The dry density–water content relationship follows a parabolic curve. The peak point of each curve in the figure represents a mix with the optimal water content determined by the maximum dry density using the specified method. Table 8 presents the maximum dry density, the corresponding wet density and air content, and the mix proportion with optimal water content. The added water contents are calculated accordingly using Eq. (3). The mass of each ingredient in 1 m3 concrete can be evaluated using the wet density and mix proportion listed in Table 8.

The experimental results demonstrate that for the same mixes, the M-P method results in lower optimal water content than the M-VB method. The experimental work disclosed that the mixes with the optimum water content determined by the M-P and M-VB methods were not lumpy during mixing, as expected. Hence, they met the requirements of roller compactability and paver placeability. However, for the mixes with optimal water contents determined by the M-VB method, a large number of voids were observed on the surface of the samples (see Fig. 5a). This is also affirmed by the resulting air content in Table 8. Obviously, the M-VB method is not an appropriate method, in terms of concrete durability.

The development of the PMC-to-OPCC composite specimen and the curing and testing methods are presented in Section 4. The direct shear bond strengths of mixes, the proportions of which (Table 8) were determined by the M-P and the M-VB method, are much lower than OPCC-to-OPCC bond strength (4.07 MPa), as detailed in Figs. 9 and 10 and Section 4.2. The laboratory work revealed that most composite cylinders of mixes determined by the M-P method developed voids at their interfaces. Nevertheless, the wet density of PMC samples, tested after the direct shear bond strength test, was close to the wet density derived in the M-Pand the M-VB test, as listed in Table 8.

It is clear from the above that the mixes with the water contents determined by the M-P and M-VB methods are too dry, resulting in insufficient cement paste moistening the interface and hence low bond strength. Therefore both approaches are not suitable for mix design for bonded RCC overlays.

It should be pointed out that the low bond strengths for the mixes, i.e. M1(M-P), M2(M-P) and M3(M-P), M1(M-VB) and M2(M-VB) and M3(M-VB), were partially attributed to the low SBR content. However the mix of M5(M-VB), containing 10% SBR, with the optimal water content determined by the M-VB method, still produced lower direct shear bond strength and splitting strength than the corresponding strengths of OPCC-to-OPCC.

Table 8
Mix proportion determined by M-P and M-VB and M-L method

compaction method	mix ID	mix parameters			mix proportion							
		maximal dry density kg/m³	wet density kg/m³	air content %	cement	PFA	MTK	CA	FA	SBR	added water	SF
M-P method	M1(M-P)	2304	2446	1.62	1	0.224	0.082	2.167	1.140	0.064	0.267	0
	M2(M-P)	2319	2467	1.56	1	0.224	0.082	2.167	1.140	0.064	0.278	0.080
	M3(M-P)	2342	2492	2.34	1	0.224	0.082	2.167	1.140	0.064	0.288	0.241
M-VB method	M1(M-VB)	2226	2376	3.85	1	0.224	0.082	2.167	1.140	0.064	0.288	0
	M2(M-VB)	2247	2405	3.15	1	0.224	0.082	2.167	1.140	0.064	0.309	0.080
	M3(M-VB)	2280	2438	3.87	1	0.224	0.082	2.167	1.140	0.064	0.309	0.241
	M5(M-VB)	2386	2485	5.1	1	0	0	1.518	1.013	0.217	0.048	0.184
M-L method	M4(M-L)	2352	2454	2.92	1	0	0	1.518	1.013	0.217	0.056	0
	M5(M-L)	2424	2539	3.04	1	0	0	1.518	1.013	0.217	0.072	0.184

3.2. Standard Proctor compaction method

Since the mixes determined by the M-P and M-VB methods were deemed to be too dry, the S-P compaction method, which requires lower compaction effort, was investigated. According to British Standard [5], the S-P method requires rammer compaction in 3 layers and 27 blows for each layer. The mixes of M4 and M5 in Table 7, which contain solid SBR of 10% to cement by weight, were used to examine the suitability of the S-P method.

The relationship between dry density and total water content by the S-P method is illustrated in Figure 2. It is seen that the optimal water (total water) contents are 110kg for mix of M4(S-P) and 130kg for mix of M5(S-P), respectively. The corresponding mix of M5 (M-VB) value obtained by the M-VB method was 105kg. It is obvious that there is an increase in the optimal water content determined by the S-P method than by the M-VB method. However, the two mixes, M4(S-P) and M5(S-P), with the optimal water content determined by the S-P method became lumpy during mixing, indicating that it was unsuitable for pavers. Hence this method is not an appropriate approach for mix design. The bond strengths of mixes with the optimal water content determined by the S-P method were not investigated because of the poor workability mix.

In civil engineering practice, materials with the optimal water content determined by the S-P method are usually suitable for light roller compaction. In this study the S-P method was employed and compared with the method proposed in the following section. It is envisaged that the appropriate roller compactor corresponding to the proposed method can be selected, based on the optimal water contents derived by both methods.

3.3. Modified Light compaction method

Since the compaction effort of the M-P and the M-VB methods is too high, and that of the S-P too low, the optimal compaction effort should lie in the range between the M-P and the S-P compaction test. In this study, the devices for the S-P compaction test with different compaction efforts were used, as follows: Five layers and twenty-seven blows per layer (5 × 27 blows), four layers and twenty-seven blows per layer (4 × 27 blows), four layers and twenty blows per layer (4 × 20 blows), three layers and twenty seven blows per layer (3 ×27 blows, namely S-P method). The relationships of dry density and total water content for M5 (Table 7) by different compaction effort are illustrated in Fig. 3. It was observed that dry densities decrease with decreasing compaction effort. However, the optimal water contents increase with decreasing compaction effort. The compaction effort of 4 x 20 blows seemed to be appropriate because its optimal water content (120 kg) was close to that (130 kg) of 3 × 27 blows (S-P method), and the mix did not become lumpy during mixing.

M4 (Table 7) was used to confirm the hypothesis by employing both the compaction effort of 4 x 20 blows and the 3 × 27 blows (S-P method). The dry density vs. total water content is plotted in Fig. 4. It was found that the optimal water content (total water content) determined by 4 × 20 blows is 110 kg, the same as 3 × 27 blows (S-P method).

The above two paragraphs indicate that the mixes M4 and M5, with optimal water content determined by 4 × 20 blows, are suitable for ‘‘roller compactability’’ for light rollers. The laboratory observation showed that M4 with the water content of 110 kg, and M5 with the water content of 120 kg, behaved as a granular material, suggesting that they were suitable for ‘‘paver placeability’’.

The method with 4 × 20 compaction effort using S-P devices is named as modified light (M-L) compaction method. It had been experimentally verified for ‘‘roller compactability’’ and ‘‘paver placeability’’ by varying the mix ingredients as presented in the following section.

The direct shear bond strength and splitting tensile bond strength of PMC-to-OPCC composite specimens of M5(M-L) are illustrated in Section 4.2. From Figs. 9 and 10, the direct shear bond strength and the splitting tensile bond strength of M5(M-L) were measured to be 5.47

MPa and 2.21 MPa, respectively, higher than the OPCC-to-OPCC bond strength.

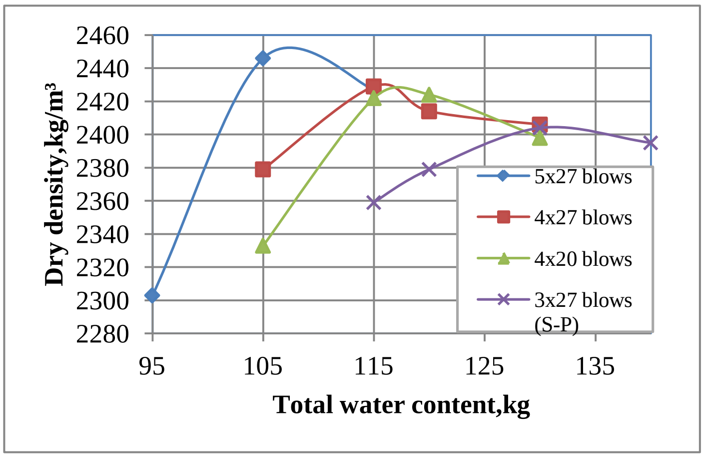

Fig.3 Dry density vs. total water content of M5 (Table 7) by different compaction efforts

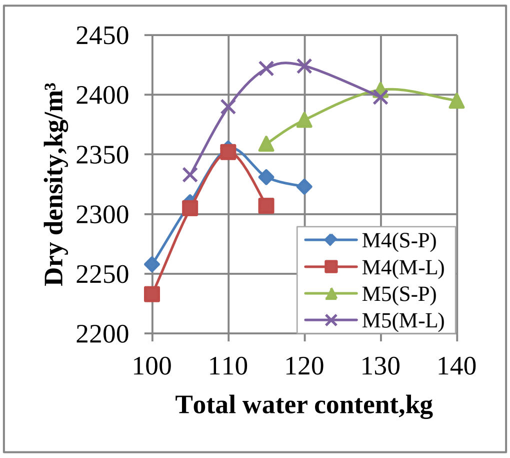

Fig.4 Dry density vs. total water content of M4 and M5 (Table 7) by the S-P and M-L methods

3.4. Experimental verification for M-L method

The M-L compaction method proposed above was experimentally verified for "roller compactability" and "paver placeability" by nine mixes using 4.75mm – 14mm size aggregate, super-plasticizer, sand contents of 40% and 50% and different types of polymers (SBR, PVA and SBR-PVA hybrid polymer). The nine mixes are listed in Table 9.

In addition to the mixes listed in Table 9, the M-L method was first verified by using the mix of M5 (Table 7) but with maximum aggregate size of 14mm. The optimal water content (total water content) was 115kg. The behaviour of the mix was granular, not lumpy. This proved that the M-L method is suitable for mixes with maximum aggregate size of 14mm.

Table 9

Mixes for verifying M-L compact method

Mix ID	cement kg	CA kg	FA kg	SBR kg	PVA kg	superplasticizer kg	total water kg	SF kg
M6	635	964	643	138	6.35	0	variable	117
M7	635	964	643	138	12.7	0		117
M8	635	964	643	138	19.05	0		117
M9	635	804	804	138	0	0		0
M10	635	804	804	138	0	0		117
M11	635	804	804	138	12.7	0		117
M12	635	804	804	0	6.35	9.53		117
M13	635	804	804	0	12.7	9.53		117
M14	635	804	804	69	12.7	0		117

There are many different products of the PVA family. A particular PVA was used by Hughes and Lubis [15] to modify the cement mortar. High flexural strength and high bond strength with steel reinforcement were achieved using a small roller compactor in the laboratory. Details about the PVA product are not available in the paper. In this study, two PVA products, GH-17S and NH-18S, were experimentally investigated. The experimental results indicated that the introduction of NH-18S did not enhance the concrete bond strength and flexural strength. On the contrary, the inclusion of GH-17S improved the bond strength and therefore GH-17S was adopted.

It should be noted that the PVA and superplasticizer dosages are defined in terms of cement ratio by weight, while for SBR is defined as the solid ingredient to cement by weight. The mixes for verification contained different dosages of PVA and SBR–PVA hybrid polymer and superplasticizer, and different sand ratios, as listed in Table 9. The experimental results, namely the relationships between dry density and total water content are plotted in Fig. 6. The maximum dry density, the corresponding wet density, air content and the mix proportion having optimal water content are listed in Table 10. The ingredient quantity for 1 m3 concrete can be evaluated easily by the wet density and mix proportion in Table 10.

The laboratory investigation showed that the mixes containing PVA were sticky. The more the PVA used, the poorer the workability became. With 3% added PVA, the M8 was considered too sticky to be spread and placed by asphalt pavers, while the remaining eight mixes in Table 10 with the optimal water content determined by the M-L method appeared to behave as granular materials during mixing and processing and were deemed to meet the requirements of ‘‘roller compactability’’ and ‘‘paver placeability’’.

In addition, the compacted samples of the above nine mixes with optimal water content were solid, with no visible voids observed, indicating that the mixes met the durability requirements. Six compacted samples, mixes M9–M14 listed in Table 9, with optimal water content determined by the M-L method are illustrated in Fig. 5b, showing no visible voids present on the surface. As detailed in Tables 8 and 10, the air contents of concrete with optimal water content determined by the M-L method were about 3%, slightly higher than conventional concrete (1%).

After analyzing the experimental results in Tables 8 and 10, it was observed that the optimal water content (the added water to cement ratio) increases with the increase of any of the following parameters: sand ratio, steel fibre content and PVA dosage.

As abovementioned, the mix of M8(M-L) containing 10%SBR and 3%PVA exhibited poor workability. However the PVA dosage of 1% may not be sufficient to provide the adhesion required. Therefore, the PVA dosage of 2% was considered to be optimum and could potentially achieve high bond strength. Its proportion is recorded in Table 10 under M7(M-L). The corresponding 28-day direct shear bond strength of PMC-to-OPCC composite specimens was later tested to be 6.07 MPa, and the 28-day splitting tensile bond strength was 2.56 MPa (see Figs. 9 and 10). Both are deemed to be much higher than the OPCC-to-OPCC bond strength.

In summary, the M-L method, 4-layer compaction and 20 blows for each layer with the S-P devices, is an appropriate mix design method for steel fibre reinforced roller-compacted polymer modified bonded overlays.

(a)

(b)

Figure 5. (a) Compacted sample with optimal water content by M-VB method: Visible voids are present on surface. (b) Six compacted samples of mixes M9–M14 (Table 9) with optimal water content by M-L method: No visible voids are present on all samples.

Table 10

Experimental results of mixes with optimal water content using M-L compaction method

	mix parameters			mix proportion							
mix ID	maximal dry density kg/m³	wet density kg/m³	air content %	cement	CA	FA	SBR	PVA	superplasticizer	added water	SF
M6(M-L)	2348	2479	2.98	1	1.518	1.013	0.217	0.01	0	0.103	0.184
M7(M-L)	2334	2464	3.32	1	1.518	1.013	0.217	0.02	0	0.103	0.184
M8(M-L)	2299	2445	2.68	1	1.518	1.013	0.217	0.02	0	0.135	0.184
M9(M-L)	2343	2456	2.30	1	1.266	1.266	0.217	0	0	0.064	0
M10(M-L)	2355	2482	3.16	1	1.266	1.266	0.217	0	0	0.094	0.184
M11(M-L)	2289	2427	3.96	1	1.266	1.266	0.217	0.02	0	0.119	0.184
M12(M-L)	2380	2531	2.01	1	1.266	1.266	0	0.01	0.015	0.244	0.184
M13(M-L)	2327	2490	2.94	1	1.266	1.266	0	0.02	0.015	0.268	0.184
M14(M-L)	2296	2455	3.23	1	1.266	1.266	0.109	0.02	0	0.209	0.184

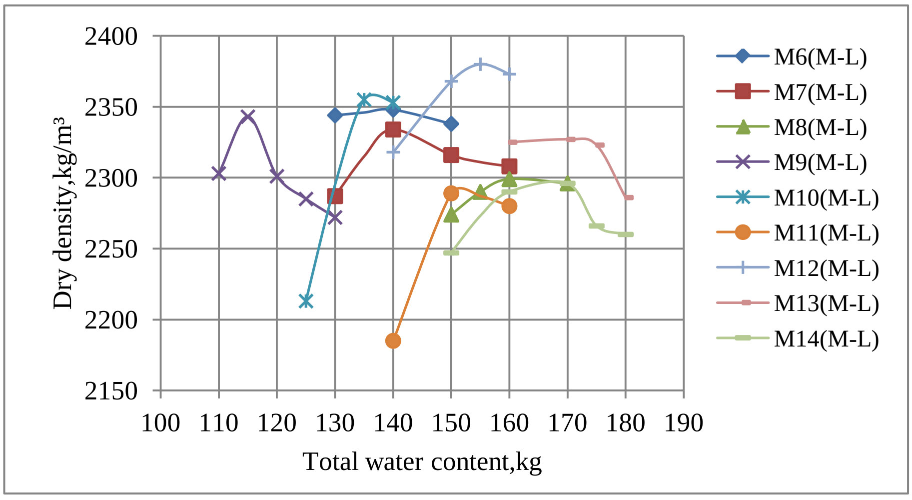

Figure 6. Relationship of dry density and total water content of mixes shown in Table 9, obtained by the M-L compaction method

4. Bond Strength

4.1. Preparation of PMC-to-OPCC composite samples

The interface between overlay and old concrete pavement is undergoing shear, tension and compression under vehicular and thermal loading during its service life. Therefore the bond performance of PMC-to-OPCC composite specimen is accordingly evaluated by both, direct shear bond strength and splitting tensile bond strength. In this study, OPCC cylinders of 100 mm diameter and 100 mm height were used as a base, while the OPCC prismatic bases were 50 × 150 × 50 mm. The OPCC cylinders were topped up by PMC material of 100 mm and 80 mm height, while the PMC part of the prismatic block was 50 _ 150 _ 50 mm. All the OPCC bases were at least 14 days old prior to usage. About four hours after casting, the surface of OPCC base was brush-roughened to remove surface mortar to expose coarse aggregate. The interfacial texture of OPC cylinder and block is shown in Fig. 7a and b, respectively. The specimen surface appeared to be similar to the treated surface of an old concrete pavement in field shown in Fig. 7c. The average texture depth of OPCC cylinder and block surfaces were 1.75 mm and1.65 mm, respectively, measured by the sand patch method [16].

Various methods [10,17–19] have been developed for RCC specimen formation in laboratory. In this study, a device comprising a vibrator and steel plates designed to fit the specimen sizes was specifically manufactured for specimen formation. This is pictured in Fig. 7f.

The surfaces of OPCC bases were dampened, and then covered with a wet cloth for about 30 min prior to being overlaid by PMC to ensure surface-dry saturated condition. Compaction of PMC was carried out in two layers. Each layer was 40–50 mm thick. The vibrating compaction lasted 20–30 s per layer, until mortar formed a ring around the perimeter of the moulds. The surface of each layer was roughened before accepting the next layer. Three specimens were fabricated for each mix. Specimens were covered with polythene sheets to minimize moisture evaporation after finishing compaction. The composite specimens were de-moulded in 24 h, and then cured in water for 5 days, followed by 22-day air curing (the temperature in the laboratory varied between 18 and 23oC and the relative humidity between 52% and 60%).

The PMC wet densities, tested by weighing in air and water after the bond strength test, were close to those determined by the corresponding compaction methods described earlier. The experimental set-up for direct shear bond strength and splitting tensile bond strength adopted, is illustrated in Fig. 8b and d, and the corresponding diagrams in Fig. 8a and c. The set-up for direct shear bond strength is similar to that used in the USA [3]. The loading rates for the direct shear tests and tensile splitting tests were conducted at 0.39 kN/s and 1.4 kN/s, respectively. The direct shear bond strength was evaluated by applying the maximum load divided by the area undergoing shear, while the splitting tensile strength was evaluated by following equation:

$$\sigma_c = \frac{2P}{\pi A} \tag{7}$$

Where: σ_c is the splitting tensile strength (MPa); P is the maximum load (N); A is the area of split section (mm^2).

The strength for each mix was evaluated by averaging the three test readings obtained from the three specimens.

(a) (b) (c) (d) (e) (f)

Figure 7. (a) Treated surface of OPCC cylinder base, (b) treated surface of OPCC block base, (c) treated surface of an old concrete pavement in use [3], (d) PMC-to-OPCC composite cylinder, (e) PMC-to-OPCC composite block, (f) devices for specimen formation.

(a) (b) (c) (d)

Figure 8. (a) PMC-to-OPCC composite cylinder demonstrating direct shear bond strength test (unit: mm). (b) PMC-to-OPCC composite cylinder under test. (c) PMC-to-OPCC composite block for splitting tensile bond strength test (unit: mm). (d) PMC-to-OPCC composite block under test.

4.2. Bond strength

The tested direct shear bond strength and splitting tensile bond strength at the age of 28 days and 42 days are illustrated in Figs. 9and 10, respectively. It is seen that M5(M-L) in Table 8 and M7(M-L) in Table 10 exhibited much higher bond strengths than OPCC-to-OPCC.

Careful observations during bond strength tests showed that all failed planes developed through the interfaces, in both direct shear bond and splitting tensile bond strength tests. This indicated that both bond strength tests were appropriate to evaluate the bond strength of composite specimens. It was observed that nearly 50% of the failed section area was covered by the bonded material in the PMC-to-OPCC composite specimens made of M5(M-L) and M7(M-L), in which high bond strength was achieved. In contrast, when the bond strength was low, the interface did not contain traces of the bonded material.

The direct shear strengths of M5(M-L) and OPCC, carried out using the same set-up were 9.32 MPa and 7.0 MPa, respectively. The 42-day direct shear bond strength of M7(M-L) was 6.81 MPa, very close to the OPCC direct shear strength of 7.0 MPa. This indicates that a very high bond strength was achieved with SBR–PVA hybrid polymer modified cement concrete.

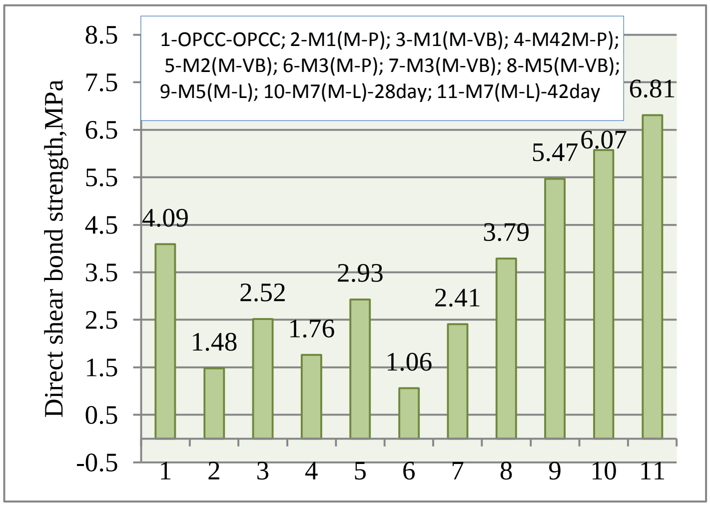

Figure 9. Direct shear bond strength of PMC-to-OPCC

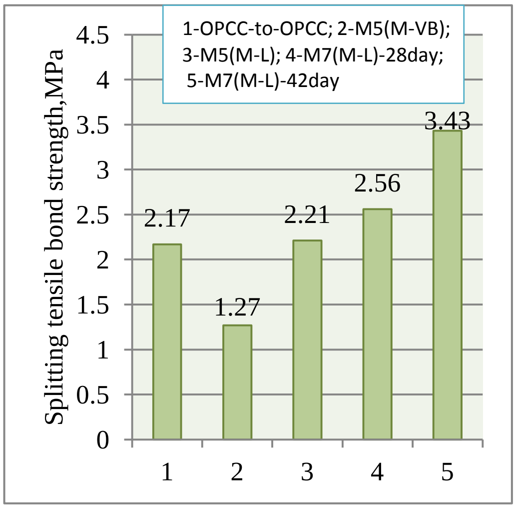

Figure 10. Splitting tensile bond strength of PMC -to-OPCC

5. Essentials of the M-L Compaction Method

The optimal water content determined by the maximum dry density was originally proposed in soil compaction to evaluate compactability. The philosophy is the more the solid content in a unit volume the higher the strength. More solid content in soil means less water and air void content, which could adversely affect the soil strength. However, strength of concrete is not only dependent on air content, but also on water content and cement hydration product. This means that for the same mix proportion, concrete having maximum solid content may not guarantee the highest strength. To the authors' best knowledge, the hypothesis for utilizing the soil compaction method in RCC mix design is not available to date. Therefore the M-L compaction method needs to be experimentally verified.

For this purpose six mixes, i.e. M9–M14, as listed in Table 9, were tested, not only by the M-L compaction method for determining the optimal water content, but also tested at 28 days for splitting tensile strength. The container was first moistened with a concrete release agent, and then excess oil was carefully removed with a tissue. The surface of each compacted layer was roughened before accepting the next layer. After compaction, sample and container were covered with polythene sheets and de-moulded in 24 hours. Samples were cured in water for 5 days, followed by 22 days curing in air under normal laboratory conditions. The experimental results indicated that four out of six mixes reached the highest strength at optimal water content, corresponding to maximum dry density. The other two mixes did not exhibit the same phenomena although only one sample was actually prepared for each strength test.

The results of M9 and M11 in Table 9, the splitting tensile strengths and dry densities corresponding to different water contents (total water content, W_{T1}, in 1 m^3 concrete), are plotted in Figure 11. It is observed that the optimal water content corresponding to the maximum dry density determined by the M-L compaction method also guarantees the highest strength. Hence the M-L method is justified.

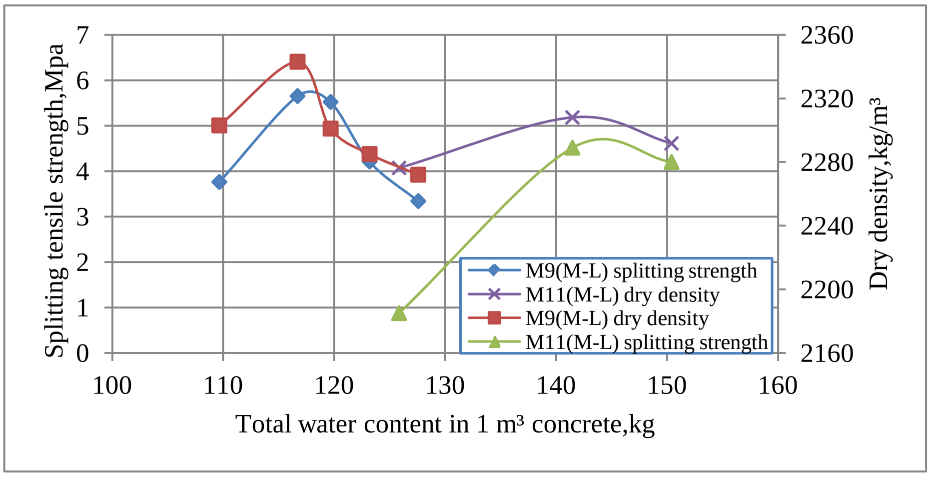

Figure 11. Compacted samples of M9 and M11 by the M-L method reaching highest splitting tensile strength and maximum dry density at the same water content.

5. Conclusions

Summarizing the discussion above, the following conclusions can be drawn:

1. Mixes with optimal water content determined by the S-P method were deemed to be unsuitable for pavers, as they turned lumpy during mixing. Hence, the method itself is not recommended as a suitable method for roller compaction and paver placement of fibre reinforced polymer modified concrete. On the contrary, mixes with optimal water content determined by the M-P and M-VB methods were found to be not-lumpy during mixing. Therefore at first, they appeared to have met the requirements for roller "compactability" and paver "placeability". However, the bond strength was lower than the previously defined criteria. In addition, a large number of voids were detected on the surface of the samples made with the M-VB method after de-moulding. Therefore, the M-P and M-VB method was deemed to be inappropriate in terms of durability.

2. A new mix design method for determining the optimal water content, the M-L method, is proposed for steel fibre reinforced, roller-compacted, polymer modified, bonded concrete overlays. This was experimentally verified. This method employs devices of the Standard Proctor compaction test and a compaction effort of 4 layers and 20 hammer blows for each layer.

3. The air contents of mixes with optimal water content determined by the M-P method are approximately 3%, slightly higher than that of the corresponding conventional concrete.

4. Two types of mixes suitable for asphalt paver placement and roller compaction were developed: They were the SBR and the SBR- PVA hybrid polymer modified cement concrete mixes with the optimal water contents determined by the M-L method. Both mixes achieved good bond with old concrete substrate. The bond strengths were considerably higher than the conventional concrete to conventional concrete bond strength.

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References

[1] Delatte, Norbert J. et al, Investigating performance of bonded concrete overlays, Journal of performance of constructed facilities, May 1998, pp.62-70.

[2] Delatte, Norbert J.; Sehdev, A.; 2003, Mechanical properties and durability of bonded-concrete overlays and ultrathin whitetopping concrete, Journal of Transportation Engineering, 2003, pp.16-23.

[3] Harrington, D. et al, 2008, Guide to Concrete Overlays", Second edition, National Concrete Pavement Technology Centre, USA, September 2008.

[4] Mokarem, D.W., Galal K.A., Sprinkel, M.M., 2007. Performance Evaluation of Bonded Concrete Pavement Overlays after 11 Years, Transportation Research Record, Vol.2007 No.2005, pp3-10.

[5] BS 1377-4:1990, 2002, Methods of test for Soils for civil engineering purposes—part 4: Compaction-related tests, British Standard Institute, UK.

[6] ACI Committee 211, 2002, Guide for selecting proportions for no-slump concrete (ACI 211.3R-02), ACI, USA.

[7] ASTM C 1170-06, 2006, Standard test method for determining consistency and density of roller-compacted concrete using a vibrating table, ASTM Committee C09, USA.

[8] ACI Committee 207, 1999, Roller-Compacted Mass Concrete (ACI 207.5R-99), ACI, USA.

[9] Kagaya,M.; Suzuki,T.; Kokubun,S.; Tokuda, H.;2001, A study on mix proportions and properties of steel fibre reinforced roller-compacted concrete for pavements, (Translation from Proceedings of JSCE, No.669/V-50, February 2001)

[10] Neocleous,K.;Angelakopoulos,H.;Pilakoutas,K.; Guadagnini,M.; 2011, Fibre-reinforced roller-compacted concrete transport pavements, Proceedings of the Institution of Civil Engineers, UK, Transport 164, May 2011 Issue TR2, pp97-109.

[11] Koutselas,K. 2011,Sustainable 'Green' overlays for strengthening and rehabilitation of

concrete pavements, PhD Thesis, Civil Engineering, Faculty of Engineering and Computing, Coventry University UK.
[13] ASTM C 1439-99, 1999, Standard test methods for polymer-modified mortar and concrete, ASTM Committee C-9, USA.
[14] ASTM C 138/C138M-01a, 2001, Standard test method for density (unit weight), yield, and air content (Gravimetric), ASTM Committee C09, USA.
[15] Hughes, B.P.; Lubis, B.; 1996, Roller compacted sheets of polymer modified mortar, Cement and Concrete Composites, 18(1996), pp41-46.
[16] BS 598-105:1990, 1998, Sampling and examination of bituminous mixtures for roads and other pavement areas- part 105: Methods of tests for determination of texture depth, UK.
[17] ASTM C 1176-05, 2006, Standard practice for making roller-compacted concrete in cylinder moulds using a vibrating table, ASTM Committee C09, USA.
[18] ASTM C 1435/C 1435M-06, 2006, Standard practice for moulding roller-compacted concrete in cylinder moulds using a vibrating hammer, ASTM Committee C09, USA.
[19] Filho,J.,M.; Paulon,V.A.; Monteiro,P.J.M.; Andrade,W.P.D.; 2008,Development of laboratory device to simulate roller-compacted concrete placement, ACI Materials Journal, March-April 2008,Vol.105,No.2,pp125-130.

Further reading

[12] National Concrete Pavement Technology Centre, USA; 2010, Guide for roller-compacted concrete pavements, Aug. 2010.