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Optimizing the mix design of cold bitumen emulsion mixtures using response surface methodology

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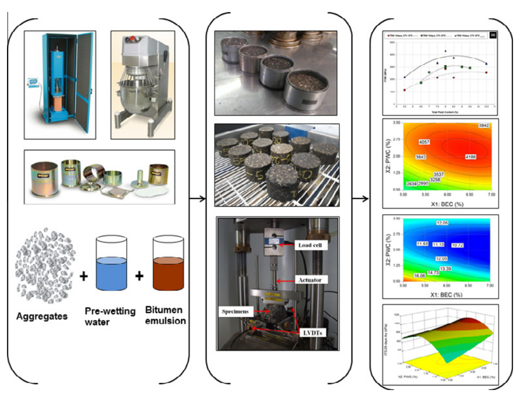
HIGHLIGHTS

- Optimization of CBEM was obtained using RSM.
- RSM was used to study the interaction between mix design parameters of CBEM.
- Optimum mix design proportions, BEC and PWC, tend to be only slightly influenced by CT.
- A good agreement between experimental results and predicted values was found.

GRAPHICAL ABSTRACT



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ABSTRACT

Cold mix asphalt (CMA) has been increasingly recognized as an important alternative worldwide. One of the common types of CMA is cold bitumen emulsion mixture (CBEM). In the present study, the optimization of CBEM has been investigated, to determine optimum proportions to gain suitable levels of both mechanical and volumetric properties. A central composite design (CCD) with response surface methodology (RSM) was applied to optimize the mix design parameters, namely bitumen emulsion content (BEC), pre-wetting water content (PWC) and curing temperature (CT). This work aimed to investigate the interaction effect between these parameters on the mechanical and volumetric properties of CBEMs. The indirect tensile stiffness modulus (ITSM) and indirect tensile strength (ITS) tests were performed to obtain the mechanical response while air voids and dry density were measured to obtain volumetric responses.

The results indicate that the interaction of BEC, PWC and CT influences the mechanical properties of CBEM. However, the PWC tended to influence the volumetric properties more significantly than BEC. The individual effects of BEC and PWC are important, rather than simply total fluid content which is used in conventional mix design method. Also, the results show only limited variation in optimum mix design proportions (BEC and PWC) over a range of CT from 10 °C to 30 °C. The variation range for optimum BEC was 0.42% and 0.20% for PWC. Furthermore, the experimental results for the optimum mix design were corresponded well with model predictions. It was concluded that optimization using RSM is an effective approach for mix design of CBEMs.

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1. Introduction

Several benefits are gained from using cold mix asphalt (CMA) instead of hot mix asphalt (HMA). The benefits include conservation of materials and energy, preservation of the environment and reduction in cost [1,2]. One of the common types of CAM is cold bitumen emulsion mixture (CBEM). Although the advantages of CMAs are real, they attract relatively little attention and are considered inferior to HMA as structural layers due to their less satisfactory performance [3]. This may be at least partially due to the wide variation in available mix design procedures, tests and criteria. Some authorities and researchers have proposed mix design procedures, based on empirical formulae, laboratory tests or past experience [1,4]. However, there is no global agreement on mixture design method or structural design methodology for CMAs [5]. Thus, it is clear that optimization of mixture parameters has to be made more consistent in order to promote the technology [4] whereas the variations in material proportions will generate differences in performance [6]. It is therefore essential to design and optimize mixture components in order to achieve appropriate properties [4,7].

Most of the studies reported in the literature on CBEMs have focused on using the method adopted by the Asphalt Institute (Marshall Method for Emulsified Asphalt Aggregate Cold Mixture Design), with some modifications [1,8]. There would therefore appear to be potential to explore the use of a statistical tool to optimize the mixture design of CBEMs.

In response to the above need, the present study has been undertaken in order to develop a performance based mix design incorporating a statistical approach using response surface methodology (RSM). RSM is used as the optimization technique to adjust the mixture parameters of CBEM to achieve acceptable mechanical strength and suitable volumetric properties. The study aimed to investigate the interaction effect of mixture parameters on the mechanical and volumetric properties of CBEM. RSM and a three-level factorial experimental design have been applied to satisfy these conditions. The central composite design (CCD) method has been used. CCD is a fractional factorial experimental design able to provide the relationship between responses and factors over a range of factor levels [9,10].

RSM is regularly applied in disciplines such as concrete [11–13], material and mechanical engineering technologies [14–16]. Recently, there has been growing attention to the application of RSM in asphalt research [17–24]. Chávez-Valencia et al. [17] also implemented RSM to evaluate the ageing phenomenon of bituminous binder in HMA. Haghshenas et al. [18] studied the effects of frequency, temperature and their interaction, on rutting of HMA using RSM. Hamzah et al. [19] used RSM to optimize the binder content of warm mix asphalt incorporating Rediset by evaluating the volumetric and strength properties of mixes. Kavussi et al. [20] investigated the effect of aggregate gradation, hydrated lime content and Sasobit content on moisture damage of warm mix asphalt. An experimental study [21] used RSM to assess the effects of aggregate gradation and lime content on stripping of HMA in terms of the strength and stiffness. Also, Khodaii et al. [22] evaluated the effects of aggregate gradation, lime content, Sasobit content and binder content on stripping potential of warm mix asphalt. RSM was used to investigate the effects of short term aging on asphalt binder rheological properties [23]. A laboratory study [24] assessed the properties of stone mastic asphalt mixtures incorporating waste polyethylene terephthalate using RSM.

There is therefore a potential benefit to apply RSM as an alternative approach for the optimization of mix design parameters in CBEMs.

Table 1
Independent parameters and their coded levels for CCD.

Parameters	Code	Unit	Coded parameter levels		
			−1	0	+1
BEC	X_1	%	5.0	6.0	7.0
PWC	X_2	%	0.5	2.0	3.5
CT	X_3	°C	10	20	30

(−1) refers low level; (0) refers to mean level; (+1) refers to high level.

Table 2
Matrix of experimental design by CCD.

Run No.	Mix design parameters			Total fluid content (%)
	BEC (%)	PWC (%)	CT (°C)	
Mix 01	5.0	3.5	10	8.50
Mix 02	7.0	0.5	10	7.50
Mix 03	7.0	3.5	10	10.5
Mix 04	5.0	0.5	10	5.50
Mix 05	6.0	2.0	10	8.00
Mix 06	6.0	3.5	20	9.50
Mix 07	6.0	0.5	20	6.50
Mix 08	7.0	2.0	20	9.00
Mix 09	6.0	2.0	20	8.00
Mix 10	6.0	2.0	20	8.00
Mix 11	6.0	2.0	20	8.00
Mix 12	6.0	2.0	20	8.00
Mix 13	5.0	2.0	20	7.00
Mix 14	6.0	2.0	20	8.00
Mix 15	6.0	2.0	20	8.00
Mix 16	6.0	2.0	30	8.00
Mix 17	7.0	3.5	30	10.50
Mix 18	7.0	0.5	30	7.50
Mix 19	5.0	3.5	30	8.50
Mix 20	5.0	0.5	30	5.50

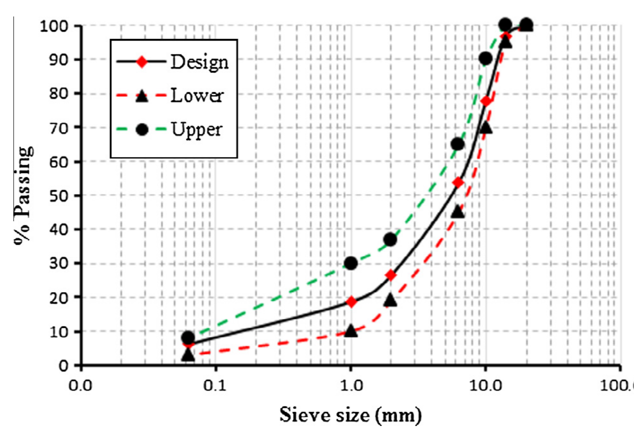

Fig. 1. Limestone aggregate gradation.

Table 3
Physical characteristics of limestone aggregate.

Properties	Value
Density – oven dried	2.68 Mg/m^3
Density – saturated surface dried	2.69 Mg/m^3
Density – apparent	2.70 Mg/m^3
Water absorption	0.4%
Aggregate Abrasion Value (AAV)	11.0
Polished Stone Value (PSV)	31
Los Angeles Coefficient (LA)	28