

Optimization of stability and flow of modified asphalt concrete using ceramic tile waste and quarry dust

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Abstract

Ceramic wastes have contributed hugely to environmental pollution in our societies, mostly because it is non-biodegradable and not reused in any significant quantity presently. Research has confirmed the feasibility of incorporating these wastes into cement concrete and asphalt concrete production. In this study, the use of ceramic tile dust as a replacement for quarry dust in hot asphalt mix was investigated and polynomial model equations have been developed for predicting the Stability and flow of asphalt mix incorporating ceramic tile dust as a full or partial replacement for quarry dust filler. The model was formulated Using Scheffe's simplex lattice theory. 15 design points were picked from the boundaries of the simplex and tests from these design points were used for model fitting. Another 15 points were picked within the simplex and test results from these points were used for model testing. Results of the laboratory tests show that the incorporation of ceramic tile dust improves the stability and flow of the resulting asphalt mix, and this was attributed to the pozzolanic property of ceramic tile dust. The model has been tested and confirmed to be adequate based on statistical values from F-statistics, Analysis of Variance, and normal probability distribution plot of model residuals. Hence, the proposed models were adequate for the prediction/optimization of stability and flow of asphalt concrete incorporating ceramic tile dust as a partial replacement for filler.

Keywords: asphalt concrete, ceramic tile dust, Scheffe's simplex lattice, stability and flow, quarry dust

Kulcsszavak: aszfaltbeton, kerámia cseréppor, Scheffe-féle szimplex rács, stabilitás és áramlás, kőbányapor

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1. Introduction

In our societies today, industrial, and domestic wastes generated yearly have contributed to huge environmental problems. Recycling these industrial waste and by-products is a key to achieving sustainable development, which should be a national priority. Some of these wastes could be recycled and used afterwards as building materials by the construction industry. To produce asphalt concrete (AC) and cement concrete (CC), many industrial wastes and by-products have been used with great advantages because of study discoveries. These materials consist of substances like fly ash [1], ground granulated blast-furnace slag [2, 3], and quarry dust [4, 5].

Industries that produce ceramic products, such as sanitary ware, earthenware, electrical insulators, bricks, floor tiles, wall tiles, and roof tiles, produce ceramic wastes. Some of these wastes are produced throughout the manufacturing process due to production errors, size discrepancies, non-standard goods, glazing errors, and more. Additionally, ceramic waste could be produced during shipping and distribution processes as well as during construction and demolition at the project site. Ceramic waste makes up about 30% of all demolition wastes [6] and continues to make up 54% of all building and demolition wastes [7]. It has been reported that up to 30% of the output of the ceramic industries is wasted [8]. These non-biodegradable wastes are not significantly recycled, instead they are dumped in landfills [9-14].

According to the research that is currently available, ceramic wastes are primarily adopted in AC either as a replacement for aggregate [15-18] or as a replacement for filler [19-21], and these practices are successful. Recycled ceramic aggregate was adopted in a study [22] to partially replace conventional aggregate in hot asphalt mix. The studies were run at both full scale in an asphalt plant and scaled quantities in a laboratory. The replacement was up to 30%. The results indicate that recycled ceramic aggregate can be used to produce hot asphalt mixtures that largely satisfy the mechanical requirements for use as road binders. The Author further stated that its addition leads to increased binder and filler contents and consequently increased indirect tensile strength and resistance to plastic deformation. In a similar study, [23] reported that replacing up to 20% conventional aggregate with recycled ceramic tiles improved the marshal stability and resilient modulus strength by 25% and 13.5% respectively. Studies on the use of ceramic waste as filler material also show positive results. For instance, in a study carried out by [24], the replacement of conventional limestone filler with ceramic waste powder improves the mechanical properties of hot asphalt mix in terms of Marshal stability, resistance to moisture, fatigue life and rutting resistance. Several other studies have also reported the improved mechanical properties of AC. This happened because of the replacement of conventional filler material with ceramic waste powder [19, 21].

Asphalt mix design and optimization are very important aspects of asphalt mix production because the properties of asphalt concrete depend on the mix proportions of the constituents. The most economical and efficient way of achieving an optimum mix is the use of statistical and mathematical procedures known as response surface methodology (RMS) [25]. RMS usually requires the formulation of model equations for responses through the design of experiments and optimization of these responses using the formulated model equations [26]. These responses are usually mechanical properties. There are presently no such model equations for asphalt mix incorporating ceramic waste as either aggregate or filler. In this study, the mathematical model equation was formulated using Scheffe's simplex lattice theory [27], for the prediction of stability and flow properties of AC with partial replacement of conventional filler material with ceramic tile dust.

2. Materials and methods

2.1 Materials

Five materials: bitumen, coarse aggregate, fine aggregate, quarry dust (GD) and ceramic tile dust (CTD) were sourced from Rivers State of Nigeria, prepared, and used in this study. To obtain CTD, waste ceramic walls and floor tiles were acquired from a ceramic tile dealer in the local Market in bags. They were mechanically crushed and sieved into the required size (passing 75 μm sieve) as determined by [23]. The fine aggregate was sourced from a river sand mining site. It was air-dried to expel moisture, then sieved with a 4.5mm sieve to eliminate undesired materials. The size separation between fine and coarse aggregate was carried out by [23]. The coarse aggregate used was granite with a maximum size of 12 mm. In this investigation, penetration grade 60/70 bitumen was acquired from a reliable company. This bitumen complied with the specifications for usage as asphaltic cement in the medium traffic category. Quarry dust material was subjected to a sieve (75 μm sieve) to obtain the required particle size as determined by [23]. Preliminary tests were carried out on the materials and the respective results were collected.

2.2 Methods

The following procedures were applied to achieve the aim of this study: preparation and characterization of asphalt mix constituents; design of experiment using Scheffe's simplex lattice theory; production of test samples based on the designed experiment; and testing of samples. The test results were then used to formulate and validate the required Scheffe's regression model equations. Details of the procedures are as follows.

2.2.1 Design of Experiment

The Design of the experiment was based on Scheffe's simplex lattice theory. The Explanations of the principles and procedures of using the theory can be found in numerous literatures [24-29]. The asphalt mix in this study had five components and the data were to be fitted into the second-degree polynomial expression. Hence, a {5,2} simplex lattice was adopted. Scheffe's

reduced polynomial for a {5,2} simplex lattice is as given in Eq. 1 and Eq. 2, where S_T and F are the responses to be modelled which are stability and flow respectively for this study. U_i are the pseudo components of the model and θ_i are the model coefficients to be determined using experimental data [24-28].

$$S_T = \theta_1 U_1 + \theta_2 U_2 + \theta_3 U_3 + \theta_4 U_4 + \theta_5 U_5 + \theta_{12} U_1 U_2 + \theta_{13} U_1 U_3 + \theta_{14} U_1 U_4 + \theta_{15} U_1 U_5 + \theta_{23} U_2 U_3 + \theta_{24} U_2 U_4 + \theta_{25} U_2 U_5 + \theta_{34} U_3 U_4 + \theta_{35} U_3 U_5 + \theta_{45} U_4 U_5 \quad (1)$$

$$F = \theta_1 U_1 + \theta_2 U_2 + \theta_3 U_3 + \theta_4 U_4 + \theta_5 U_5 + \theta_{12} U_1 U_2 + \theta_{13} U_1 U_3 + \theta_{14} U_1 U_4 + \theta_{15} U_1 U_5 + \theta_{23} U_2 U_3 + \theta_{24} U_2 U_4 + \theta_{25} U_2 U_5 + \theta_{34} U_3 U_4 + \theta_{35} U_3 U_5 + \theta_{45} U_4 U_5 \quad (2)$$

Generation of test data for the determination of model coefficients for a {5,2} simplex lattice polynomial requires data from at least 15 design points within the simplex [24, 26, 27]. Therefore, 15 design points were picked from the surface of the simplex for the generation of data that would be used for the model fitting. These included 5 points from the 5 vertices (Fig. 1) of the simplex which represented the pure blends. The remaining 10 points were selected from halfway between two vertices on the boundaries of the simplex. As control points, 15 other points (Fig. 2) were also selected within the simplex (not at the boundaries). Data from the control points were used for the model testing. Lower and upper boundaries for each component were taken as 0 and 1 respectively while the sum of all components at each test point equals 1. The generated design matrix in pseudo components at the design and control points are presented in Table 1 and Table 2 respectively.

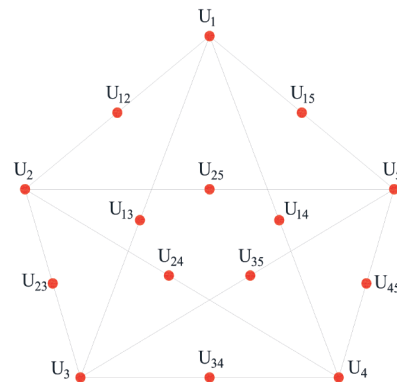


Fig. 1 Scheffe's simplex plot for pseudo components
1. ábra Scheffe szimplex ábrája pszeudo komponensek esetén

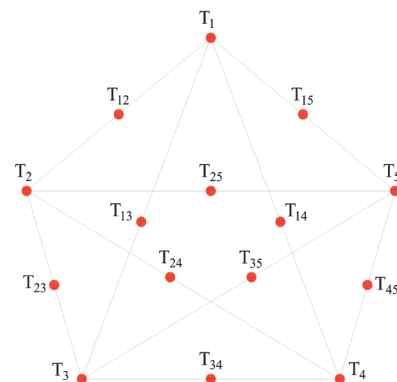


Fig. 2 Scheffe's simplex plot for actual components
2. ábra Scheffe szimplex ábrája a tényleges komponensekre vonatkozóan

Design Points	Pseudo Component					Response V_{exp}	Actual component				
	U1	U2	U3	U4	U5		T1 Asphalt	T2 Granite	T3 Sand	T4 QD	T5 CTD
1	1.00	0.00	0.00	0.00	0.00	V_1	0.040	0.480	0.4608	0.01536	0.00384
2	0.00	1.00	0.00	0.00	0.00	V_2	0.045	0.5133	0.4207	0.0126	0.00840
3	0.00	0.00	1.00	0.00	0.00	V_3	0.050	0.5463	0.3816	0.0089	0.01330
4	0.00	0.00	0.00	1.00	0.00	V_4	0.055	0.5788	0.3433	0.0046	0.01830
5	0.00	0.00	0.00	0.00	1.00	V_5	0.060	0.611	0.306	0.0230	0.0000
6	0.50	0.50	0.00	0.00	0.00	V_{12}	0.043	0.497	0.441	0.0140	0.0060
7	0.50	0.00	0.50	0.00	0.00	V_{13}	0.045	0.5132	0.4212	0.0121	0.00857
8	0.50	0.00	0.00	0.50	0.00	V_{14}	0.0475	0.5294	0.4021	0.0100	0.01107
9	0.50	0.00	0.00	0.00	0.50	V_{15}	0.0500	0.5455	0.3834	0.0192	0.01075
10	0.00	0.50	0.50	0.00	0.00	V_{23}	0.0475	0.5298	0.4012	0.0108	0.01085
11	0.00	0.50	0.00	0.50	0.00	V_{24}	0.0500	0.5461	0.3820	0.0086	0.01335
12	0.00	0.50	0.00	0.00	0.50	V_{25}	0.0525	0.5622	0.3634	0.0178	0.0042
13	0.00	0.00	0.50	0.50	0.00	V_{34}	0.053	0.5630	0.3620	0.0070	0.0160
14	0.00	0.00	0.50	0.00	0.50	V_{35}	0.055	0.5790	0.3440	0.0160	0.0070
15	0.00	0.00	0.00	0.50	0.50	V_{45}	0.058	0.5950	0.3250	0.0140	0.0090

Table 1 Design matrix showing pseudo and actual components of design points for model fitting
1. táblázat A tervezési mátrix, amely a modellillesztéshez használt tervezési pontok pszeudo- és tényleges összetevőit mutatja

Control Points	Pseudo Component					Response V_{exp}	Actual component				
	U1	U2	U3	U4	U5		T1 Asphalt	T2 Granite	T3 Sand	T4 QD	T5 CTD
1	0.333	0.333	0.333	0.000	0.000	V_{c1}	0.045	0.5132	0.4210	0.0123	0.0085
2	0.333	0.333	0.000	0.333	0.000	V_{c2}	0.0467	0.5240	0.4082	0.0109	0.0102
3	0.333	0.000	0.333	0.333	0.000	V_{c3}	0.0483	0.5350	0.3952	0.0096	0.0118
4	0.333	0.333	0.000	0.000	0.333	V_{c4}	0.0483	0.5347	0.3958	0.0170	0.0041
5	0.250	0.250	0.250	0.250	0.000	V_{c5}	0.0475	0.5296	0.4016	0.0104	0.01096
6	0.250	0.250	0.250	0.000	0.250	V_{c6}	0.0490	0.5380	0.3920	0.0150	0.0060
7	0.250	0.250	0.000	0.250	0.250	V_{c7}	0.0500	0.5458	0.3827	0.0139	0.0076
8	0.000	0.250	0.250	0.250	0.250	V_{c8}	0.0525	0.5624	0.3629	0.0123	0.0100
9	0.300	0.100	0.200	0.200	0.200	V_{c9}	0.0495	0.5426	0.3865	0.0132	0.0083
10	0.200	0.200	0.100	0.300	0.200	V_{c10}	0.0505	0.5491	0.3787	0.0125	0.0093
11	0.200	0.200	0.200	0.100	0.300	V_{c11}	0.0505	0.5491	0.3788	0.0148	0.0069
12	0.200	0.200	0.200	0.200	0.200	V_{c12}	0.0500	0.5459	0.3825	0.0129	0.0088
13	0.150	0.250	0.200	0.200	0.200	V_{c13}	0.0500	0.5480	0.3800	0.0130	0.0090
14	0.200	0.200	0.150	0.250	0.200	V_{c14}	0.0050	0.5480	0.381	0.0130	0.0090
15	0.250	0.200	0.200	0.200	0.150	V_{c15}	0.0490	0.5390	0.390	0.0130	0.0090

Table 2 Design matrix showing pseudo and actual components at control points
2. táblázat Tervezési mátrix, amely a pszeudo és a tényleges komponenseket mutatja az ellenőrzési pontokon

2.2.2 Transformation of Pseudo to Actual Components

From Scheffe’s polynomial theory, the relationship between a set of pseudo components and actual components at a test point for the responses is as given in Eq. 3 where T is a column matrix of real component ratios, U is a column matrix of pseudo components at a test point and A is a square matrix of actual components corresponding to the pure blends at the five vertices of the simplex.

$T = A^T U$ (3)

The Mix compositions at the vertices of the simplex were selected based on the author’s experience and data from the

literature. From existing literature, [30, 31] the Optimum Bitumen Content (OBC) of an asphalt mix always falls between 4% - 6% of the total weight/volume of the asphalt mixture, making the aggregate content to be limited to 94% - 96% of the total mix. For aggregate combination, coarse aggregate usually falls in the range of 50% - 65% of the aggregate content; thus, limiting the fine aggregate content to 35% - 50%. Total filler content is usually limited to the range of 4% - 7% of the fine aggregate content while CTD content varies between 0% - 80% of the filler content. The ratio of bitumen (T_1), coarse aggregate (T_2), fine aggregate (T_3), quarry dust (T_4) and CTD

(T_5) at vertex U_1 , were therefore selected respectively as: [0.040: 0.4800: 0.4608: 0.01536: 0.00384]. Mix ratios at the other four vertices (U_2 , U_3 , U_4 , and U_5) were selected respectively as: [0.045: 0.5133: 0.4207: 0.0126: 0.0084], [0.050: 0.5463: 0.3816: 0.0089: 0.0133], [0.055: 0.5788, 0.3433: 0.0046: 0.0183], [0.060: 0.6110: 0.3060: 0.0230: 0.0000]. By arranging these in a matrix form, the square matrix, A was achieved as:

$$A = \begin{bmatrix} 0.040 & 0.480 & 0.4608 & 0.01536 & 0.00384 \\ 0.045 & 0.5133 & 0.4207 & 0.0126 & 0.0084 \\ 0.050 & 0.5463 & 0.3816 & 0.0089 & 0.0133 \\ 0.055 & 0.5788 & 0.3433 & 0.0046 & 0.0183 \\ 0.060 & 0.6110 & 0.3060 & 0.0230 & 0.0000 \end{bmatrix} \quad \text{and}$$

by transposing matrix A , A^T was deduced as

$$A^T = \begin{bmatrix} 0.040 & 0.045 & 0.050 & 0.055 & 0.060 \\ 0.4800 & 0.5133 & 0.5463 & 0.5788 & 0.6110 \\ 0.4608 & 0.4207 & 0.3816 & 0.3433 & 0.3060 \\ 0.01536 & 0.0126 & 0.0089 & 0.0046 & 0.0230 \\ 0.00384 & 0.0084 & 0.0133 & 0.0183 & 0.0000 \end{bmatrix}$$

Substituting A^T into Eq. 2 gave

$$\begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \end{pmatrix} = \begin{pmatrix} 0.040 & 0.045 & 0.050 & 0.055 & 0.060 \\ 0.4800 & 0.5133 & 0.5463 & 0.5788 & 0.6110 \\ 0.4608 & 0.4207 & 0.3816 & 0.3433 & 0.3060 \\ 0.01536 & 0.0126 & 0.0089 & 0.0046 & 0.0230 \\ 0.00384 & 0.0084 & 0.0133 & 0.0183 & 0.0000 \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \end{pmatrix} \quad (4)$$

Transformation of pseudo components to real components was carried out using Eq. 4 as follows:

In response V_{12} ;

$$\begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \end{pmatrix} = \begin{pmatrix} 0.040 & 0.045 & 0.050 & 0.055 & 0.060 \\ 0.4800 & 0.5133 & 0.5463 & 0.5788 & 0.6110 \\ 0.4608 & 0.4207 & 0.3816 & 0.3433 & 0.3060 \\ 0.01536 & 0.0126 & 0.0089 & 0.0046 & 0.0230 \\ 0.00384 & 0.0084 & 0.0133 & 0.0183 & 0.0000 \end{pmatrix} \begin{pmatrix} 0.5 \\ 0.5 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0.043 \\ 0.497 \\ 0.441 \\ 0.0140 \\ 0.006 \end{pmatrix}$$

In the same way, at response V_{13} ,

$$\begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \end{pmatrix} = \begin{pmatrix} 0.040 & 0.045 & 0.050 & 0.055 & 0.060 \\ 0.4800 & 0.5133 & 0.5463 & 0.5788 & 0.6110 \\ 0.4608 & 0.4207 & 0.3816 & 0.3433 & 0.3060 \\ 0.01536 & 0.0126 & 0.0089 & 0.0046 & 0.0230 \\ 0.00384 & 0.0084 & 0.0133 & 0.0183 & 0.0000 \end{pmatrix} \begin{pmatrix} 0.5 \\ 0 \\ 0.5 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0.045 \\ 0.5132 \\ 0.4212 \\ 0.0121 \\ 0.00857 \end{pmatrix}$$

Real components for all the design points and control points as given in Table 1 and Table 2, were computed using the same procedure.

2.2.3 Preparation and Testing of Specimens

Hot mix Asphalt concrete was batched by weight making use of the real component ratios in Table 1 and Table 2. A total of 30 different samples were prepared. 15 sample types were taken to represent design points and the results from these points were used for the model fitting while another 15 different sample types were prepared using data from the control points and their results were used for the model testing. All mixing and compaction of asphalt concrete were carried out by ASTM D8079-16 [32]. Stability and flow tests were carried out by the procedures described in ASTM D6927 [33], the standard test method for Marshall stability and flow of bituminous mixtures. Using the Marshall testing machine, the Marshall stability values were recorded when the specimens were loaded at constant strain (50.8 mm per minute) to failure and at a preheated temperature of 60 °C. While the stability

test at the failure point was in progress, the dial gauge was used to measure the corresponding vertical deformations known as Marshall flow values of the specimen expressed in units of 0.25 mm.

2.2.3 Determination of Model Coefficients

From the principle of Scheffe's theory, the number of design points required for model fitting as shown in Table 1 must be equal to the number of model coefficients in the polynomial equation (Eq. 1) [24-29]. From this relationship, the coefficient of the polynomial equation can be related to the expected experimented responses at the design points as in Eq. 5. In this study, the model coefficients were obtained based on Eq. 5. using the experimental responses at the design points.

$$\theta_i = v_i \quad \text{and} \quad \theta_{ij} = 4v_{ij} - 2v_i - 2v_j \quad (5)$$

3. Results

3.1 Material characterisation

Particle size distribution of fine and coarse aggregates used in this study are given in Fig. 3 and 4 respectively while volumetric properties of asphalt concrete components are presented in Table 3., Tables 4 and 5 present the properties of bitumen used and compound compositions of CTD respectively.

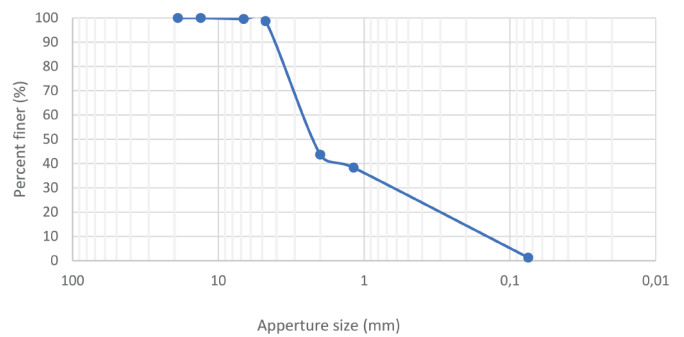


Fig. 3 Particle size distribution curve for fine river sand
3. ábra Finom folyami homok szemcseméret-eloszlási görbéje

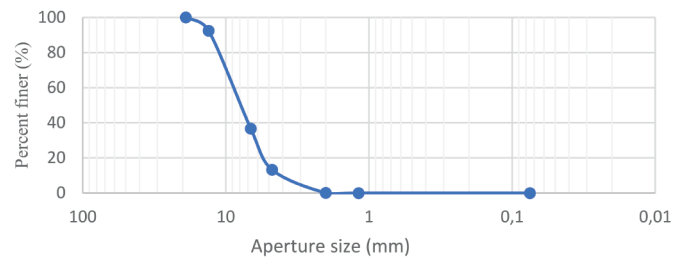


Fig. 4 Particle size distribution curve for granite
4. ábra Gránit szemcseméret-eloszlási görbéje

Property	Sand	Granite	Bitumen	QD	CTD
Specific gravity	1.64	2.64	1.04	1.47	1.18
Bulk density (kg/m³)	1635	1386	1040	1588	1373
Coefficient of uniformity	16.67	2.14			
Coefficient of gradation	1.13	1.08			

Table 3 Asphalt concrete's component volumetric properties
3. táblázat Az aszfaltbeton komponenseinek térfigorati tulajdonságai

Property	Unit	Test Method	Value
Softening point	°C	BS EN 1427	53°C
Penetration	0.1 mm	BS EN 1426	68
Flash point	°C	BS EN 22592	250°C

Table 4 Bitumen properties
4. táblázat A bitumen tulajdonságai

Compound	% Composition by mass
SiO ₂	53.57
V ₂ O ₅	0.09
Cr ₂ O ₃	0.09
MnO	0.08
Fe ₂ O ₃	8.27
Co ₃ O ₄	0.05
Nb ₂ O ₃	0.01
SO ₃	0.48
CaO	15.29
K ₂ O	2.94
Al ₂ O ₃	15.47
Ta ₂ O ₅	0.03
TiO ₂	1.72
ZnO	0.44
BaO	0.22
ZrO ₂	0.53
WO ₃	0.01

Table 5 Chemical composition of CTD
5. táblázat A CTD kémiai összetétele

S/N	Stability factor	No of Stability deflections (0.042kN)		Stability (kN)		Average stability (kN)	Corrected stability (kN)	No of flow deflections (0.01mm)		Flow (mm)		Average flow (mm)	Time to failure (s)	
		a	b	a	b			a	b	a	b		a	b
V1	0.948	160	185	6.720	7.770	7.245	6.868	347.4	347.0	3.474	3.470	3.472	12.480	15.320
V2	0.855	194	249	8.148	10.458	9.303	7.954	268.3	288.3	2.683	2.883	2.783	11.970	13.110
V3	0.861	175	254	7.350	10.668	9.009	7.757	218.6	238.6	2.186	2.386	2.286	16.240	14.550
V4	0.849	270	303	11.340	12.726	12.033	10.216	250.6	230.6	2.506	2.306	2.406	16.240	12.240
V5	0.855	195	206	8.190	8.652	8.421	7.200	310.5	316.5	3.105	3.165	3.135	14.290	10.930
V6	0.874	265	234	11.130	9.828	10.479	9.159	225.8	245.8	2.258	2.458	2.358	15.820	14.190
V7	0.880	185	223	7.770	9.366	8.568	7.540	210.0	250.0	2.100	2.500	2.300	13.360	12.480
V8	0.912	398	305	16.716	12.810	14.763	13.464	284.3	264.3	2.843	2.643	2.743	10.900	11.920
V9	0.981	244	280	10.248	11.760	11.004	10.795	227.0	223.0	2.270	2.230	2.250	11.600	13.950
V10	0.973	330	356	13.860	14.952	14.406	14.017	330.1	310.1	3.301	3.101	3.201	12.070	10.670
V11	1.003	237	364	9.954	15.288	12.621	12.659	317.0	319.0	3.170	3.190	3.180	14.840	12.180
V12	0.880	185	202	7.770	8.484	8.127	7.152	383.1	379.1	3.831	3.791	3.811	9.550	10.990
V13	1.003	380	352	15.960	14.784	15.372	15.418	281.5	291.5	2.815	2.915	2.865	10.300	10.600
V14	0.813	179	180	7.518	7.560	7.539	6.129	337.2	317.2	3.372	3.172	3.272	15.770	12.220
V15	0.941	368	434	15.456	18.228	16.842	15.848	370.6	376.6	3.706	3.766	3.736	11.270	13.180

Table 6 Stability and flow experimental test results at design points
6. táblázat Stabilitási és áramlási kísérletek vizsgálati eredményei a tervezési pontokon

3.2 Experimental Responses for Stability and Flow

Table 6 presents the experimental results for stability, S_T and flow, F of asphalt mix at the 15 design points while Table 7 shows the same stability, S_T and flow, F results but with their respective pseudo and actual mix components. These values would be used for the determination of coefficients of the proposed stability, S_T and flow, F models. Maximum and minimum obtainable responses within the factor space of the simplex would be defined by these values. Experimental responses at the control points are also presented in Table 8 and will be used for the model testing.

3.3 Model Formulation

Stability and flow experimental data from Tables 7 and 8 were used to fit the simplex lattice polynomial model equations in Eq. 1 based on the relationships in Eq. 5. The resulting model coefficients for Stability, S_T were as follows: $\theta_1=6.868$; $\theta_2=7.954$; $\theta_3=7.757$; $\theta_4=10.216$; $\theta_5=7.200$; $\theta_{12}=6.992$; $\theta_{13}=0.910$; $\theta_{14}=19.688$; $\theta_{15}=15.044$; $\theta_{23}=24.646$; $\theta_{24}=14.296$; $\theta_{25}=-1.700$; $\theta_{34}=25.726$; $\theta_{35}=-5.398$; $\theta_{45}=28.560$. While that of Flow, F were: $\theta_1=4.325$; $\theta_2=3.180$; $\theta_3=3.135$; $\theta_4=5.025$; $\theta_5=5.515$; $\theta_{12}=4.850$; $\theta_{13}=8.480$; $\theta_{14}=-7.600$; $\theta_{15}=-0.800$; $\theta_{23}=1.590$; $\theta_{24}=3.710$; $\theta_{25}=-3.310$; $\theta_{34}=5.040$; $\theta_{35}=+0.980$; $\theta_{45}=-3.280$. Therefore, if the five vertices of the {5,2} simplex lattice are represented in the pseudo form as U_1 , U_2 , U_3 , U_4 , and U_5 respectively, then the resulting Scheffé's polynomial model equations for predicting Stability, S_T and Flow, F are given as:

$$S_T = 6.868U_1 + 7.954U_2 + 7.757U_3 + 10.216U_4 + 7.200U_5 + 6.992U_1U_2 + 0.9100U_1U_3 + 19.688U_1U_4 + 15.044U_1U_5 + 24.646U_2U_3 + 14.296U_2U_4 - 1.700U_2U_5 + 25.726U_3U_4 - 5.398U_3U_5 + 28.560U_4U_5 \tag{6}$$

$$F = 4.325U_1 + 3.180U_2 + 3.135U_3 + 5.025U_4 + 5.515U_5 + 4.850U_1U_2 + 8.480U_1U_3 - 7.600U_1U_4 - 0.800U_1U_5 + 1.590U_2U_3 + 3.710U_2U_4 - 3.310U_2U_5 + 5.040U_3U_4 + 0.980U_3U_5 - 3.280U_4U_5 \tag{7}$$

N	Pseudo Component					Actual component					Stability (kN)	Flow (mm)
	U ₁	U ₂	U ₃	U ₄	U ₅	T ₁	T ₂	T ₃	T ₄	T ₅		
V ₁	1	0	0	0	0	0.040	0.480	0.4608	0.01536	0.00384	6.868	3.472
V ₂	0	1	0	0	0	0.045	0.5133	0.4207	0.0126	0.00840	7.954	2.783
V ₃	0	0	1	0	0	0.050	0.5463	0.3816	0.0089	0.01330	7.757	2.286
V ₄	0	0	0	1	0	0.055	0.5788	0.3433	0.0046	0.01830	10.216	2.406
V ₅	0	0	0	0	1	0.060	0.611	0.306	0.0230	0.0000	7.200	3.135
V ₆	0.5	0.5	0	0	0	0.043	0.497	0.441	0.0140	0.0060	9.159	2.358
V ₇	0.5	0	0.5	0	0	0.045	0.5132	0.4212	0.0121	0.00857	7.540	2.300
V ₈	0.5	0	0	0.5	0	0.0475	0.5294	0.4021	0.0100	0.01107	13.464	2.743
V ₉	0.5	0	0	0	0.5	0.0500	0.5455	0.3834	0.0192	0.01075	10.795	2.250
V ₁₀	0	0.5	0.5	0	0	0.0475	0.5298	0.4012	0.0108	0.01085	14.017	3.201
V ₁₁	0	0.5	0	0.5	0	0.0500	0.5461	0.3820	0.0086	0.01335	12.659	3.180
V ₁₂	0	0.5	0	0	0.5	0.0525	0.5622	0.3634	0.0178	0.0042	7.152	3.811
V ₁₃	0	0	0.5	0.5	0	0.053	0.5630	0.3620	0.0070	0.0160	15.418	2.865
V ₁₄	0	0	0.5	0	0.5	0.055	0.5790	0.3440	0.0160	0.0070	6.129	3.272
V ₁₅	0	0	0	0.5	0.5	0.058	0.5950	0.3250	0.0140	0.0090	15.848	3.736

Table 7 Stability and flow test trial mix results with pseudo and actual components at design points
7. táblázat Stabilitási és áramlási próbakeverékek eredményei pszeudo- és tényleges komponensekkel a tervezési pontokon

N	Pseudo Component					Actual component					Response Symbol	Experimented S _T (kN)	Experimented F (mm)
	U ₁	U ₂	U ₃	U ₄	U ₅	T ₁	T ₂	T ₃	T ₄	T ₅			
1	0.333	0.333	0.333	0.000	0.000	0.0450	0.5132	0.4210	0.0123	0.0085	VC1	11.697	2.502
2	0.333	0.333	0.000	0.333	0.000	0.0467	0.5240	0.4082	0.0109	0.0102	VC2	12.536	2.712
3	0.333	0.000	0.333	0.333	0.000	0.0483	0.5350	0.3952	0.0096	0.0118	VC3	13.156	2.617
4	0.333	0.333	0.000	0.000	0.333	0.0483	0.5347	0.3958	0.0170	0.0041	VC4	9.399	2.692
5	0.250	0.250	0.250	0.250	0.000	0.0475	0.5296	0.4016	0.0104	0.0110	VC5	13.368	2.717
6	0.250	0.250	0.250	0.000	0.250	0.0490	0.5380	0.3920	0.0150	0.0060	VC6	9.815	2.802
7	0.250	0.250	0.000	0.250	0.250	0.0500	0.5458	0.3827	0.0139	0.0076	VC7	13.288	3.063
8	0.000	0.250	0.250	0.250	0.250	0.0525	0.5624	0.3629	0.0123	0.0100	VC8	13.597	3.697
9	0.300	0.100	0.200	0.200	0.200	0.0495	0.5426	0.3865	0.0132	0.0083	VC9	12.821	2.805
10	0.200	0.200	0.100	0.300	0.200	0.0505	0.5491	0.3787	0.0125	0.0093	VC10	13.417	3.128
11	0.200	0.200	0.200	0.100	0.300	0.0505	0.5491	0.3788	0.0148	0.0069	VC11	12.047	3.064
12	0.200	0.200	0.200	0.200	0.200	0.0500	0.5459	0.3825	0.0129	0.0088	VC12	13.337	3.025
13	0.150	0.250	0.200	0.200	0.200	0.0500	0.5480	0.3800	0.0130	0.0090	VC13	13.396	3.127
14	0.200	0.200	0.150	0.250	0.200	0.0050	0.5480	0.3810	0.0130	0.0090	VC14	13.741	3.091
15	0.250	0.200	0.200	0.200	0.150	0.0490	0.5390	0.3900	0.0130	0.0090	VC15	13.878	2.913

Table 8 Stability (ST) and flow (F) and corresponding pseudo and actual components at control points
8. táblázat Stabilitás (ST) és áramlás (F), valamint a megfelelő pszeudo és tényleges komponensek az ellenőrzési pontokon

3.4 Model Validation

Table 9 shows model residuals which is the difference between the respective experimental response and model predicted response of stability and flow, while Fig. 5 and 6 show a normal probability plot of the same model residuals for stability and flow respectively. The test of the adequacy of the proposed stability and flow models was carried out using the F-test and Analysis of Variance based on experimental and model-predicted responses at the 15 control points. Tables 10 and 12 present the result of the F-test while Tables 11 and 13 show the results of the Analysis of Variance for stability and flow respectively. The null hypothesis for both tests was that there is no significant difference between experimental and

model-predicted responses at the control points while the alternative hypothesis was that there is a significant difference between the two sets of values. From the F-Test results in Tables 10 and 12, the F-value for stability and flow are 1.030 and 1.058 respectively, and less than the corresponding F-Critical values which are 2.484 and 2.484. These indicate that the null hypothesis for the two tests can not be rejected. Thus, there was no significant difference between the experimental responses and their respective model-predicted responses. Thus, there was no significant difference between the experimental responses and their respective model-predicted responses. Statistics from the result of the Analysis of Variance test for stability and flow in Tables 11 and 13 also show that F-values (0.058 and 0.0033 respectively) are less than the corresponding

Control Point	Stability, ST (kN)				Flow, F (mm)			
	Experimental Response	Predicted Response	Residual	% Error	Experimental Response	Predicted Response	Residual	% Error
V _{c1}	11.367	11.143	0.224	1.973	2.502	2.544	-0.042	1.674
V _{c2}	12.857	12.899	-0.042	0.330	2.712	2.718	-0.006	0.225
V _{c3}	13.497	13.427	0.070	0.519	2.617	2.608	0.009	0.361
V _{c4}	9.551	9.600	-0.049	0.512	2.692	2.698	-0.006	0.239
V _{c5}	13.940	13.965	-0.025	0.181	2.717	2.793	-0.077	2.830
V _{c6}	9.914	9.975	-0.061	0.613	2.802	2.839	-0.037	1.303
V _{c7}	13.839	13.239	0.600	4.335	3.063	3.045	0.018	0.588
V _{c8}	13.617	13.665	-0.048	0.352	3.697	3.690	0.007	0.189
V _{c9}	12.922	12.939	-0.017	0.130	2.805	2.850	-0.045	1.597
V _{c10}	14.119	13.986	0.133	0.940	3.128	3.112	0.016	0.497
V _{c11}	11.740	11.527	0.213	1.816	3.064	3.055	0.008	0.274
V _{c12}	13.147	13.149	-0.002	0.015	3.025	3.065	-0.040	1.313
V _{c13}	13.285	13.202	0.083	0.622	3.127	3.195	-0.068	2.183
V _{c14}	13.849	13.632	0.217	1.564	3.091	3.094	-0.003	0.090
V _{c15}	13.121	13.157	-0.036	0.278	2.913	2.935	-0.022	0.761

Table 9 Model residuals for Stability and Flow at control points
9. táblázat A stabilitásra és az áramlásra vonatkozó modell maradékai az ellenőrzési pontokon

F-critical values (4.196 and 4.196), and their P-values (0.811 and 0.857) are greater than 0.05. Hence, the proposed model is adequate for the prediction of stability and flow of asphalt concrete incorporating CTD as partial replacement for filler.

	Experimental Response	Predicted Response
Mean	12.758	12.634
Variance	2.016	1.957
Observations	15.000	15.000
df	14.000	14.000
F	1.030	
P(F<=f) one-tail	0.478	
F Critical one-tail	2.484	
Mean	12.758	12.634
Variance	2.016	1.957
Observations	15.000	15.000
df	14.000	14.000

Table 10 F-test result for experimental response and model predicted response of Stability at control points
10. táblázat F-próba eredménye a kísérleti válasz és a modell által megjósolt stabilitás válaszára az ellenőrzési pontokon

Groups	Count	Sum	Average	Variance
Experimental flow	15.000	191.365	12.758	2.016
Predicted Model	15.000	189.505	12.634	1.957

Source of Variation	Sum of Square	Degree of Freedom	Mean Square	F-value	P-value	F crit
Between Groups	0.115	1.000	0.115	0.058	0.811	4.196
Within Groups	55.627	28.000	1.987			
Total	55.743	29.000				

Table 11 Analysis of Variance (single factor) for experimental and model response of Stability at control points
11. táblázat. Varianciaanalízis (egytényezős) a stabilitás kísérleti és modellválaszára az ellenőrzési pontoknál

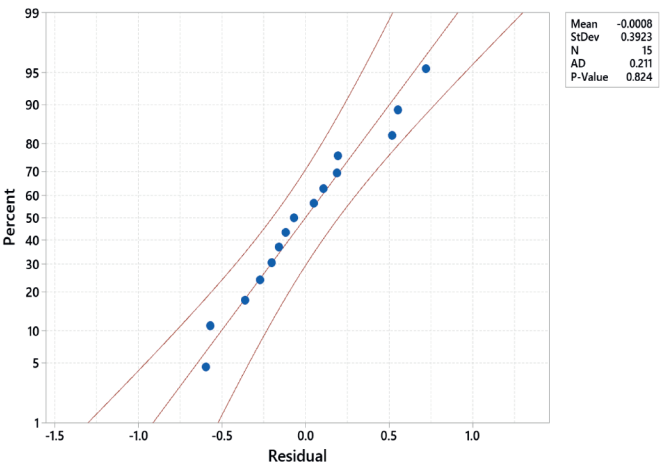


Fig. 5 Normal probability plot of stability model residuals at control points
5. ábra A stabilitási modell maradványainak normál valószínűségi ábrája az ellenőrzési pontokon

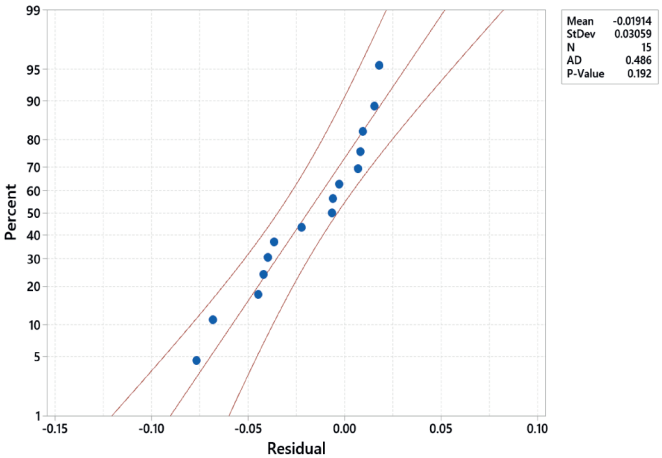


Fig. 6 Normal probability plot of flow model residuals at control points
6. ábra Az áramlási modell maradványainak normál valószínűségi ábrája az ellenőrzési pontokon

	Experimental Response	Predicted Response
Mean	2.930	2.949
Variance	0.086	0.081
Observations	15	15
df	14	14
F	1.058	
P(F<=f) one-tail	0.459	
F Critical one-tail	2.484	
Mean	2.930	2.949
Variance	0.086	0.081
Observations	15	15
df	14	14

Table 12 F - test result for experimental response and model predicted response of flow at control points
12. táblázat F - a kísérleti válasz és a modell által előre jelzett áramlási válasz vizsgálati eredménye az ellenőrzési pontokon

Groups	Count	Sum	Average	Variance
Experimental flow	15	43.954	2.930	0.086
Predicted Model	15	44.241	2.949	0.081

Source of Variation	Sum of Square	Degree of Freedom	Mean Square	F - value	P - value	F crit
Between Groups	0.003	1.000	0.003	0.033	0.857	4.196
Within Groups	2.334	28.000	0.083			
Total	2.337	29.000				

Table 13 Analysis of Variance (single factor) for experimental and model response of flow at control points
13. táblázat Varianciaanalízis (egytényezős) az áramlás kísérleti és modellválaszára az ellenőrzési pontoknál

4. Discussion

From Table 3, the specific gravity and bulk density of CTD are 1.18 and 1373 kg/m³ while the respective values for sand are 1.47 and 1588 kg/m³. These values show that the specific gravity and bulk density of CDT are slightly lower than those of QD indicating that CTD is a lighter filler material than QD. This tends to enhance the cohesion of the asphalt mix. Results from Figures 3 and 4 of the uniformity coefficient and coefficient of gradation show that both fine aggregate and coarse aggregate used are well-graded. This is because their uniformity coefficients were greater than 4.0 and their coefficient of gradation is between

1.0 and 3.0 [34]. Using well-graded aggregates also ensures the production of asphalt mix with good performance because aggregate gradation affects the performance of resulting asphalt concrete and cement concrete [35].

From Tables 7 and 8, it could be observed that asphalt mix with a high percentage of CTD is characterised by high stability and the corresponding flow. This shows that the incorporation of CTD as filler improves the stability and flow of the resulting asphalt mix. This is not surprising because it has been reported elsewhere [15, 36]. The chemical composition of CTD as presented in Table 5 is typical of ceramic waste materials [24, 27, 37] and possesses SiO₂, Fe₂O₃, CaO and Al₂O₃ as the major oxides. The presence of these compounds indicates that there are traces of tricalcium silicate, dicalcium silicate, tricalcium aluminate and tetracalcium aluminoferrite, and this is likely to be responsible for the pozzolanic property of CTD [36] which enhanced bonding in asphalt mix and hence is responsible for the improved stability and flow.

Using Scheffe's simplex lattice theory, the polynomial model equations have been formulated for predicting the stability and flow of asphalt mix incorporating CDT as a partial replacement for QD filler. The models have been tested and confirmed to be adequate based on statistical values from the F-test and Analysis of Variance. As additional confirmation, the normal probability plots of stability and flow in Figures 5 and 6 respectively show close distribution of the model residuals along the reference line and the respective plots have P-values of 0.824 and 0.192 which are far greater than the alpha level of 0.05. Hence the null hypothesis – that the model residuals follow a normal distribution – cannot be rejected and this justifies the use of Analysis of Variance [24, 27]. The quality of the proposed models can also be seen when comparing the percentage difference between experimental responses and their respective predicted model responses at the control points as presented in Table 9. The differences are generally low with the highest value being 4.335% and 2.83% for stability and flow respectively.

5. Conclusion

In this study, the use of CTD as a replacement for QD in hot asphalt mix has been investigated. Results of laboratory tests show that the incorporation of CTD improves the stability and flow of the resulting asphalt mix, and this is attributed to the pozzolanic property of CTD which enhances bonding and hence reduces void ratio. Using Scheffe's simplex lattice theory, polynomial model equations have been formulated for predicting the stability and flow of asphalt mix incorporating CDT as a partial replacement for QD filler. The models have been tested and confirmed to be adequate based on the statistical values from the F-Test, Analysis of Variance, and normal probability distribution plot of model residuals.

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