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Statistical deviations in the analysis of asphalt mix properties

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Professional paper

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Statistical deviations in the analysis of asphalt mix properties

The main purpose of this research is to establish a method for identifying statistical deviations in the analysis of properties of the asphalt mix AC 22, which are not accidental, but are caused by external factors, such as the change of standards, laboratory equipment, or staff. The analysis was made to determine deviation of correlation coefficients for properties of asphalt mixes divided into two groups. The groups are related to two time intervals, and the computation was repeated by random selection of data within the two groups, so as to determine deviations within the groups.

Key words:
analysis of asphalt mix properties, mean value, variance, correlation coefficient, p-value

Stručni rad

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Statistička odstupanja u analizama svojstava asfaltnih mješavina

Glavni je cilj ovog istraživanja pronaći metodu kojom se određuju statistička odstupanja u analizama svojstava asfaltnih mješavina AC 22, koja ne nastaju slučajno, već su uzrokovana vanjskim faktorima poput promjene normi, laboratorijske opreme ili osoblja. Proveden je proračun kako bi se odredila odstupanja koeficijenata korelacije u svojstvima asfaltnih mješavina raspoređenih u dvije skupine. Skupine se odnose na dva vremenska razmaka, a proračun je ponovljen nasumičnim odabirom podataka unutar dviju skupina, kako bi se odredila odstupanja unutar skupina.

Ključne riječi:
analiza svojstava asfaltnih mješavina, srednja vrijednost, varijanca, koeficijent korelacije, p-vrijednost

Fachbericht

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Statistische Abweichungen bei der Analyse von Asphaltmischungen

Das Hauptziel dieser Untersuchung liegt in darin, eine Methode zur Ermittlung statistischer Abweichungen in der Analyse von Asphaltmischungen AC 22, die nicht zufällig entstehen, sondern durch äußere Faktoren wie Änderungen von Normen, Laborausstattung oder Personal bedingt sind, aufzustellen. Berechnungen wurden durchgeführt, um Abweichungen der Korrelationskoeffizienten bei Eigenschaften in zwei Gruppen eingeteilter Asphaltmischungen zu ermitteln. Die Gruppen beziehen sich auf zwei Zeitspannen und die Berechnungen wurden bei zufälliger Auswahl der Werte innerhalb der zwei Gruppen wiederholt, um die Abweichungen zu bestimmen.

Schlüsselwörter:
Analyse der Eigenschaften von Asphaltmischungen, Mittelwert, Varianz, Korrelationskoeffizient, p-Wert

1. Introduction

Asphalt mixtures in road construction must be resistant to permanent deformations and cracking caused by weather conditions and fatigue. They are composed of aggregate, binder, and air voids. The preliminary selection of appropriate materials, and determination of their proportions in asphalt mixture, are needed to obtain relevant properties that influence the behaviour of asphalt. Besides the production of asphalt mixtures, it is also important to know the way in which the mixture is built in. Quality control of asphalt mixtures and asphalt layers is implemented on the basis of European standards EN.

Among other things, the behaviour of asphalt layers also depends on the quality of aggregate that is exposed to various mechanical influences and weather conditions. The basic purpose of stone grains is to transfer load from the wearing layer to the base layer.

In asphalt mixtures, bituminous binder acts as a binding material and exerts a great influence on the behaviour of asphalt mixtures. Bituminous binder is composed of a large number of similar organic compounds. Many asphalt characteristics are dependent on it: resistance to permanent deformation, compaction of asphalt layer, bulk and maximum density of mixture, etc. Main characteristics of bituminous binder that have to be investigated are the softening point (PK), and the penetration and density of binder. Bituminous binders are usually divided on the basis of different properties, most important being the softening point and penetration. Besides the conventional bituminous binder, the polymer-modified bituminous binder is also widely used in road construction. That kind of bituminous binder is modified with elastomers and plastomers to improve its properties (to increase the softening point, reduce the Fraass breaking point, increase resistance to permanent deformation, etc.) [1].

In recent years, the evolution in computer technology and automation in measurements have enabled collection of large databases and their analysis. Some of them are based on statistical methods such as the simulation and use of different analyses for the correlation, means, variances, and probability functions. Chou et al. [2] propose an approach that uses simulation models that can be employed to calculate probabilistic costs of highway bridge replacement projects. They use cumulative distribution functions as a user-friendly chart for decision makers, which can be used to assess project risks in the pre-design stage. Franz et al. [3] use different virtual simulations and correlation analyses in the field of architecture to study quantitative relations between the experience of architectural spaces and physical properties. Different authors [4, 5] have compared confidence intervals for the difference between two means when the distributions are non-normal and their variances are unknown. The Monte Carlo method [6, 7] is widely used in the field of simulation for repeated random sampling to obtain numerical results. Ozgan [8] has modelled the Marshall stability of asphalt mixtures by changing the temperature and the time of exposure to a given temperature. It turned out that a good correlation exists between experimental results, fuzzy logical model, and statistical model. This means that both the statistical model and fuzzy logical model can be used to model stability of asphalt mixtures when changing the temperature, and the time of exposure to that temperature. Likewise, Tušar and Novič [9] have analysed correlations between different asphalt properties and Marshall stability. In [10], the authors define the dependence of the variable asphalt mix grading on the realisation of physical and mechanical properties of samples, such as the stability, stiffness, density, voids content, and percent voids filled with asphalt. Tušar and Kalman [11] statistically analyse different asphalt and bituminous binder tests in order to establish the relationship between different physical asphalt properties and binder properties, and mechanical properties of asphalt mixtures.

The statistical method that can be used to establish measurement differences, and to define outliers if they exist, are described in this paper. A mathematical software is used for statistical evaluations. The primary focus is placed on the identification of changes that occur in the relationship between mechanical and physical properties of asphalt mixtures, i.e. between the Marshall stability and other properties of asphalt mixtures, and between the flow and other properties of asphalt mixtures. The statistics, such as the mean value and variance, describe the basic characteristics of the population. Changes of these statistics usually indicate a change in the population. Correlation coefficients describe the linear relationship between individual parameters of the population. Changes in the correlation coefficients do not indicate changes in the basic properties of the population but point to changes in the connections between parameters. Reasons for these changes often lie in measurement method modifications. So, if we find that correlation coefficients between two time periods change more than it would be expected due to random variations, we can conclude that changes to measurements have occurred.

We were interested in two different situations between tests differences that can be expected:

- If we divide the asphalt mixture data into two time periods, from 1998 to 2005, and from 2006 to 2009, we can find out how the change of standards in 2005 affects test results, or if the differences are due to the random variations.
- If we divide the same data randomly into two groups, like in the preceding example, we can find out which data deviate significantly and, on this basis, we can establish why the deviation occurred.

2. Data used in statistical analysis

The collected data are results obtained by tests made on samples of the asphalt mixture AC 22 in the time period from 1998 to 2009 at the Building Materials Institute (IGMAT) [12]. Asphalt mixtures were mixed with the carbonate aggregate and bituminous binder B50/70, and so all the mixtures were nominally the same. The following data were obtained by testing: softening point of bituminous binder (ring and ball test - PK), penetration (PEN), index of penetration (IP), viscosity, shares of aggregate fractions, binder content, percentage of voids in mineral aggregate filled with binder, voids content in aggregate, maximum density of aggregate, maximum density of asphalt mixture, stability, flow, Marshall quotient, bulk density of asphalt mixture, and voids content in

Table 1. Average values and standard deviations for data used in the study

Property	Average	Standard deviation
Softening point [°C]	50.8	2.8
Penetration [mm/10]	63.1	9.6
Viscosity [Pas]	204.7	45.1
Index of penetration	-0.5	0.6
Binder content [%]	3.9	0.3
Sieve 0.09 mm [%]	6.7	0.6
Sieve 0.25 mm [%]	9.5	0.9
Sieve 0.71 mm [%]	15.5	1.2
Sieve 2 mm [%]	29.2	2.1
Sieve 4 mm [%]	41.2	2.6
Sieve 8 mm [%]	59.0	2.9
Sieve 11.2 mm [%]	70.3	2.8
Sieve 16 mm [%]	83.8	2.4
Sieve 22.4 mm [%]	97.9	1.4
Bulk density of asphalt [kg/m^3]	2394	26.8
Maximum density of asphalt [kg/m^3]	2552	25.6
Voids content [%]	6.2	0.7
Percentage of the voids in the mineral aggregate filled with binder [%]	59.5	3.8
Voids content in aggregate [%]	15.2	0.7
Maximum density of aggregate [kg/m^3]	2715	36.5
Stability [kN]	11.1	2.2
Flow [mm]	3.0	0.6
Marshall quotient [kN/mm]	3.9	1.3

Table 2. P-values for average values and variances for two time periods

Properties	P-value for means	P-value for variances
Softening point (PK)	< 0.0001	0.0003
Penetration (PEN)	0.0006	0.0223
Viscosity	0.0011	0.0520
Index of penetration (IP)	< 0.0001	< 0.0001
Binder content	< 0.0001	0.0007
Sieve 0.09 mm	< 0.0001	0.0048
Sieve 0.25 mm	< 0.0001	0.2113
Sieve 0.71 mm	< 0.0001	0.0220
Sieve 2 mm	< 0.0001	0.0608
Sieve 4 mm	< 0.0001	0.3509
Sieve 8 mm	< 0.0001	0.1162
Sieve 11.2 mm	0.0568	0.0551
Sieve 16 mm	0.0017	0.0035
Sieve 22.4 mm	< 0.0001	< 0.0001
Bulk density of asphalt	0.0002	< 0.0001
Maximum density of asphalt	0.0080	< 0.0001
Voids content	< 0.0001	0.0021
Percentage of voids in mineral aggregate filled with binder	< 0.0001	0.0004
Voids content in aggregate	0.0196	0.0249
Maximum density of aggregate	0.4375	< 0.0001
Stability	0.00002	0.0049
Flow	< 0.0001	< 0.0001
Marshall quotient	< 0.0001	< 0.0001

asphalt mixture. Average values and standard deviations for all data used in the study are presented in Table 1.
We considered the data that were obtained by experiments made at the institute for building materials Igmat Ljubljana between 1998 and 2005, and between 2006 and 2009. The reason for this division is the implementation of new standards for some experiments in 2006.

3. Statistical analysis

Statistical analysis is based on comparison of mean values, variances and correlation coefficients between measured quantities. The data are divided into two groups. The division can be performed according to two time periods in which measurements were made, but also according to two groups of laboratory assistants, two laboratories, etc.
In order to determine what are the differences between correlation coefficients and what are the reasons for these differences, the correlation coefficients are calculated for two different cases:

- data are divided into two groups according to the period,
- data are randomly divided into two groups like in the first example.

The first example is basic, i.e. the one that is being checked. In the second example, we check if the data contain outliers. These outliers cause different correlation coefficients in both groups.

3.1. Correlations and simulations

The covariance S_{XY} is a statistical measure of the linear dependence between two variables. The dimensionless coefficient that describes linear dependence is the correlation coefficient r_{XY}, which is calculated using the formula:

$$r_{XY} = \frac{S_{XY}}{S_X S_Y} \tag{1}$$

where S_{XY} is the covariance, while S_X and S_Y are standard deviations of variables X and Y observed on the given sample.

Table 3. Correlation coefficients for two periods and their differences

Properties	Period 1998/2005		Period 2006/2009		Differences in r_{xy} between periods	
	r_{xy}					
	stability	flow	stability	flow	stability	flow
Softening point (PK)	0.094	0.090	- 0.041	0.146	0.135*	0.056
Penetration (PEN)	- 0.306	- 0.189	- 0.142	- 0.102	0.164*	0.087
Viscosity	0.300	0.176	0.118	0.192	0.182*	0.016
Index of penetration (IP)	- 0.160	- 0.053	- 0.211	0.093	0.051	0.146*
Binder content	0.290	0.189	- 0.166	- 0.064	0.456*	0.253*
Sieve 0.09 mm	0.361	0.244	- 0.089	0.129	0.450*	0.116*
Sieve 0.25 mm	0.322	0.116	0.156	0.278	0.166*	0.162*
Sieve 0.71 mm	0.239	0.057	0.199	0.214	0.041	0.157
Sieve 2 mm	0.143	0.016	0.077	0.135	0.066	0.119*
Sieve 4 mm	0.196	0.048	0.055	0.105	0.141	0.057
Sieve 8 mm	0.109	- 0.024	- 0.014	0.118	0.124	0.142*
Sieve 11.2 mm	0.053	- 0.059	- 0.096	- 0.008	0.148	0.051
Sieve 16 mm	- 0.053	- 0.040	- 0.103	- 0.004	0.051	0.036
Sieve 22.4 mm	0.133	0.044	- 0.088	- 0.114	0.221*	0.158*
Bulk density of asphalt	0.570	0.308	0.266	0.395	0.305*	0.087
Maximum density of asphalt	0.594	0.302	0.304	0.396	0.291*	0.095
Voids content	- 0.020	- 0.033	0.046	- 0.018	0.066	0.015
Percentage of voids in mineral aggregate filled with binder	0.185	0.128	- 0.089	0.038	0.275*	0.089
Voids content in aggregate	0.323	0.174	- 0.085	- 0.018	0.407*	0.192*
Maximum density of aggregate	0.634	0.335	0.255	0.403	0.379*	0.068

*The deviations are too large, that they could be coincidental

Since we are interested in the impact of other properties on the stability and flow, the focus is placed on the correlation that represents the impact of other properties on the stability and flow. In order to obtain critical values for the differences of correlation coefficients, we have repeatedly and randomly divided the data into two groups representing division into two periods (1777 data in the first group and 416 data in the second group), and the correlation matrix was calculated in every simulation [13].

4. Results

We have 2193 measurements for the time period between 1998 and 2009 [12] for the asphalt mixture AC 22. In each measurement, results were obtained for 22 properties (PK, PEN, viscosity, IP, binder content, stone material passing through square-aperture sieves of 0.09 mm, 0.25 mm, 0.71 mm, 2 mm, 4 mm, 8 mm, 11.2 mm, 16 mm and 22.4 mm, bulk density of asphalt mixture, maximum density of asphalt mixture, voids content, percentage of voids in mineral aggregate filled with binder, voids content in aggregate, maximum density of aggregate).

Division of measurements into two periods:
2193 measurements are divided into two groups [12]. The first group consists of 1777 measurements conducted in the time period from 1998 to 2005, and the second group consists of 416 measurements related to the time period from 2006 to 2009. First, we compared the average values and variances between the two groups where the T-test and F-test were used, respectively. It can generally be seen in Table 2 that the data from the first time period changed compared to the second time period, because p-values for averages and variances are small (< 0.05) for almost all properties, except in the case of material passing through the sieve 11.2 mm where values for the average and variance are not significantly different. Here, the p-value is defined as the probability of rejecting the null hypothesis when that hypothesis is true.
Correlation coefficients for the stability, flow and other properties of asphalt mixture are shown in Table 3 for both groups of measurements and their differences. Critical values for differences in correlation coefficients between stability and other properties of asphalt mixture are shown in Table 4. The differences that deviate little from critical values are assumed to be the result of chance. Significantly larger differences mean that changes in measurements have occurred during the time periods. The differences of correlation coefficients that exceeded critical values given in Table 4 are specially marked in Table 3. This means that the difference of correlations is statistically significant with the significance level considerably lower than 0.05. Major changes

Table 4. Critical values of differences in correlation coefficients after 10000 simulations

Properties	Values for limits of differences in r_{xy}	
	stability	flow
Softening point (PK)	0.101	0.096
Penetration (PEN)	0.092	0.106
Viscosity	0.120	0.113
Index of penetration (IP)	0.094	0.098
Binder content	0.142	0.114
Sieve 0.09 mm	0.118	0.105
Sieve 0.25 mm	0.121	0.103
Sieve 0.71 mm	0.132	0.103
Sieve 2 mm	0.152	0.109
Sieve 4 mm	0.150	0.114
Sieve 8 mm	0.167	0.128
Sieve 11.2 mm	0.170	0.121
Sieve 16 mm	0.154	0.125
Sieve 22.4 mm	0.130	0.103
Bulk density of asphalt	0.109	0.117
Maximum density of asphalt	0.113	0.140
Voids content	0.139	0.128
Percentage of voids in mineral aggregate filled with binder	0.125	0.114
Voids content in aggregate	0.157	0.134
Maximum density of aggregate	0.112	0.121
Stability		
Flow		
Marshall quotient		

Table 5. P-values of averages and variances for data randomly divided into two groups

Properties	Values for limits of differences in r_{xy}	
	stability	flow
Softening point (PK)	0.1264	0.1568
Penetration (PEN)	0.4648	0.3301
Viscosity	0.2785	0.0015
Index of penetration (IP)	0.1016	0.4885
Binder content	0.4745	0.2728
Sieve 0.09 mm	0.0755	0.4960
Sieve 0.25 mm	0.4970	0.1422
Sieve 0.71 mm	0.4725	0.034
Sieve 2 mm	0.1077	0.8421
Sieve 4 mm	0.2772	0.0567
Sieve 8 mm	0.0563	0.0383
Sieve 11.2 mm	0.0593	0.7571
Sieve 16 mm	0.3324	0.0606
Sieve 22.4 mm	0.4609	0.0204
Bulk density of asphalt	0.3121	0.0007
Maximum density of asphalt	0.2688	0.0023
Voids content	0.0841	0.0144
Percentage of voids in mineral aggregate filled with binder	0.1235	0.0817
Voids content in aggregate	0.0967	0.0193
Maximum density of aggregate	0.3160	0.0031
Stability	0.3741	0.3268
Flow	0.1471	0.4897
Marshall quotient	0.2944	0.3613

occur in: properties of bituminous binder, binder content, passing through some sieves, some properties of asphalt mixture, voids in aggregate, and maximum density of aggregate. Indeed, during this time the standards relating to test methods changed from the old JUS standards to the new European standards EN.

Prior to the use of test methods according to standards SIST EN 12697-Part 1, 2, 5, 6, 8, 34, SIST EN 1426, SIST EN 1427, SIST EN 12596, and SIST EN 12591 [14-24], the testing was conducted according to standard test methods described in JUS U.M8.082, U.M8.090, JUS U.M8.092, U.M8.102, U.M8.105, B.H8.613, B.H8.612, and B.H8.620 [25-32]. The most important differences between the standards are: preparation of Marshall specimens, difference in bulk density, maximum density of asphalt mixtures, and difference in determination of soluble and insoluble proportion of binder. The introduction of standards SIST EN also adds an additional sieve with the aperture of 0.063 mm (formerly, the smallest aperture was 0.09 mm). The determination of maximum density of asphalt mixtures according to JUS U.M8.082 required two parallel tests in solvent. However, only one test, which can be carried out in water or solvent, is allowed when maximum density of asphalt mixtures is tested according to European standard SIST EN 12697-5. The standard JUS U.M8.105 for determination of binder content prescribed supplement for insolubles, which is not included in SIST EN 12697. In fact, a specific stirrer and the use of glycerine for softening-point temperatures above 80 °C are required for the determination of softening point of binder according to SIST EN 1427. The modified preparation of specimens exerts a major influence on the determination of bulk density and stability of asphalt mixtures. A compaction hammer with the steel base is used according to European standard, while a wooden base was formerly used.

There is no standard distribution for absolute differences in correlation coefficients. For this purpose, we performed simulations in which the data were randomly divided into two groups (1777 data in the first group and 416 data in the second group). The difference in correlations were computed. The simulations were repeated 10000 times and the critical values were determined using the ranking procedure. Critical values of differences for the significance level of 0.05 are presented in Table 4.

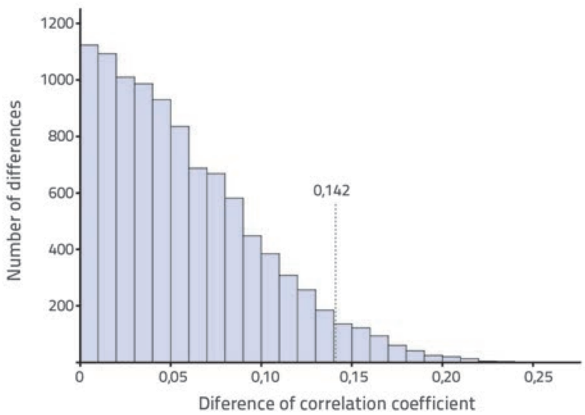

Figure 1. Frequency histogram of differences in correlation coefficients for binder content and stability

Figure 1 shows the frequency diagram of differences of correlation coefficients between the proportion of bitumen and stability in 10000 random simulations. It can be seen that the probability of exceeding the critical value of difference of 0.142 is approximately 0.05, which corresponds to the significance level. Since the actual difference for this parameter was 0.456, which is in excess of the limit value, we had to reject the null hypothesis and conclude that the difference of correlation is statistically significant with the significance level considerably below 0.05.

Division according to the randomized measurements:
2193 measurements were randomly divided into two groups, just like in previous division in two periods (1777 data in the first group and 416 data in the second group). We first examined how the two groups changed the statistical properties such as the mean value and variance for all characteristics.
At this point, it should be noted that Tables 5 and 6 are only one example of random division of measurements. P-values for the average and variance, and values for differences in correlation coefficients, changed in every simulation. The values in both tables are only an illustration of what could happen. When

Table 6. Correlation coefficients for two groups, with random division of measurements and their differences

Properties	1st group of measurements r_{xy}		2nd group of measurements r_{xy}		Differences in r_{xy} between the 1st and 2nd group of measurements	
	stability	flow	stability	flow	stability	flow
Softening point (PK)	0.064	0.223	-0.016	0.178	0.080	0.046
Penetration (PEN)	-0.287	-0.115	-0.266	-0.055	0.021	0.060
Viscosity	0.291	0.121	0.195	0.091	0.097	0.031
Index of penetration (IP)	-0.174	0.184	-0.231	0.153	0.057	0.031
Binder content	0.180	0.223	0.150	0.227	0.030	0.003
Sieve 0.09 mm	0.261	0.260	0.304	0.308	0.043	0.049
Sieve 0.25 mm	0.276	0.216	0.271	0.227	0.004	0.011
Sieve 0.71 mm	0.204	0.203	0.225	0.162	0.021	0.041
Sieve 2 mm	0.104	0.137	0.159	0.131	0.055	0.006
Sieve 4 mm	0.146	0.164	0.180	0.093	0.034	0.071
Sieve 8 mm	0.048	0.096	0.172	0.120	0.124	0.024
Sieve 11.2 mm	-0.001	-0.031	0.120	0.032	0.121	0.063
Sieve 16 mm	-0.068	0.008	-0.063	0.019	0.005	0.011
Sieve 22.4 mm	0.129	-0.088	0.070	-0.158	0.059	0.070
Bulk density of asphalt	0.470	0.340	0.480	0.334	0.011	0.007
Maximum density of asphalt	0.518	0.256	0.470	0.220	0.047	0.036
Voids content	0.025	-0.131	-0.058	-0.161	0.083	0.030
Percentage of voids in mineral aggregate filled with binder	0.101	0.204	0.142	0.220	0.040	0.016
Voids content in aggregate	0.277	0.089	0.168	0.050	0.109	0.038
Maximum density of aggregate	0.559	0.307	0.514	0.283	0.045	0.023

the procedure was repeated and the values in Table 5 were consistently very small, this was also an indicator of incorrect data in the database. These values were excluded from the analysis.

In this case, it can be seen that most of the values in Table 5 are greater than 0.05, which corresponds to the significance level. This means that, in general terms, the averages and variances are not statistically significantly different, which was also expected. In few cases when the p-value was smaller than 0.05, this can be attributed to chance. When the random division was repeated, the p-value was small for some other parameters.

Table 6 shows the correlation coefficients between stability, flow and other properties of asphalt mixture for both types of measurements and their differences. It is evident that all deviations of correlation coefficients do not exceed critical values given in Table 4. This means that correlation differences are not statistically significant, with the significance level considerably below 0.05.

5. Conclusion

The comparison of differences between correlation coefficients of simulated measurements and actual measurements, randomly divided into two groups for mixture AC 22, has shown that no measurement deviates much from other measurements. This means that where deviations occurred, they are small and are due to chance.

The comparison of differences between correlation coefficients of simulated measurements and actual measurements, which are divided into two time periods (first period runs from 1998 to 2005, and the second from 2006 and 2009), has revealed greater deviations. This means that the resulting differences are not only due to chance but also to changes in standards or any other factors that affect the measurements.

The method described in the paper enabled us to determine the effect of changes on measurements, which can not be attributed to chance but to some other external factors, such as modification of standards. We can also compare two laboratories or measurements in one laboratory at different time periods where we could estimate the impact of the replacement of machinery, staff and the like. This method can therefore be used for different kinds of problems, where the effect of various changes on different properties in asphalt pavement design is investigated. The statistical method is simple enough for wide use as it utilises only basic statistical calculations that are supported by all computer programs designed for the management, collection, and analysis of data.

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