IOSR Journal of Computer Engineering (IOSR-JCE)
e-ISSN: 2278-0661,p-ISSN: 2278-8727, Volume 23, Issue 4, Ser. II (Jul. –Aug. 2021), PP 08-24
www.iosrjournals.org

The Use and Value of DENSITY Software Package

CJ Semmelink

Abstract
Compaction related issues very often lead to construction disputes on site when the test results do not meet the specified requirements. The author was closely involved in extensive research into the material properties that influence the compactability of untreated roadbuilding materials. Untreated materials obtained from all the provinces in South Africa were used in the research. From the 21 sets of density research results obtained, the DENSITY software was developed to try and pinpoint the cause of a compaction problem with untreated material, as well as treated materials such as asphalt and Ordinary Portland Cement (OPC) mixes. The paper briefly explains the extensive research programme that was followed. This is followed by a brief discussion of ten compaction problems that were solved by means of the DENSITY software program.

Date of Submission: 06-08-2021 Date of Acceptance: 20-08-2021

I. Introduction

In Civil Engineering use is made of the measured dry density results (usually determined in kg/m^3) as determined on the compacted layer as an indicator of the bearing capacity (i.e. California Bearing Ratio (CBR)) of the compacted layer by comparing the measured dry density of the compacted layer on site with the measured dry density achieved in the laboratory using a particular laboratory test (usually either mod AASHTO compaction or vibratory table compaction) or sometimes as the percentage space occupied by particle solids (i.e. % Solid Density (SD)D)). The **DENSITY** prediction models for the different compaction properties are based on the prediction models for the different properties derived from measured results of vibratory compacted samples (single layer compaction) of 21 different untreated road-building materials ranging over the full spectrum of suitable road-building material in South Africa varying from black clay (montmorillonite)(weak) to several different types of crushed hard rock base materials) (strong), using the measured grading (after compaction) of the laboratory compacted material and the other indicator test result values of these 21 untreated road-building materials as determined in the laboratory as input information to predict the different material properties with the measured material properties, including the Maximum Dry Density (MDD), Optimum Moisture Content (OMC) and Critical Moisture Content (CMC), etc. Using the measured indicator results of the 21 different road-building materials as input information, the r^2-values of the different predicted compaction properties varied between 0.990934 (highest) and 0.946972 (lowest) with an average r^2-value of 0.975554 of the measured result. The r^2-value of a prediction model with perfect fit is 1.000000 (i.e. the measured and predicted results are then exactly the same and therefore the standard error is zero). The standard error of the predicted properties varied between 2.48% and 0.68% with an average error of 1.16%. The actual indicator test results of other materials of compacted granular layers not used to develop these **DENSITY** prediction models originally, are used as input information in the **DENSITY** program to predict the compaction properties of these compacted layers. Where the actual measured values of the compaction properties and the predicted **DENSITY** compaction properties differ, the cause of this difference is usually an indication of where the compaction problem with a particular layer is being experienced on site.

The research on these 21 untreated road-building materials collected from all over South Africa and giving these relatively high r^2-values, involved the development of new compaction and testing equipment and testing techniques, because the research aim was to simulate the compaction of these materials in a single layer (as on construction sites) as closely as possible without disturbing the aggregate grading. Altogether the research effort required a dedicated team of seven persons who worked diligently on the research project for seven years.

When the author of this paper could initially not find a definite relationship between the indicator properties and the density results he prayed to God, the Creator of the Universe, for divine guidance. He then decided to plot the measured CBR results for different density levels (i.e. from 90% to 105 % mod AASHTO) against the measured moisture contents (ranging from dry to wet) of the compacted samples of the different materials, to try and find some kind of relationship. It was then that he noticed that the measured CBR results for different mod AASHTO density levels of each material all peaked at a particular moisture content, the value for a particular material of which the moisture content value differed from material to material. The moisture contents at which the measured CBR values of each material peaked was named the Critical Moisture Content

(CMC). It was only then that the author realised that the main reason for the difference in CMC was mainly caused by the grading differences of these materials. The author did multiple regression analyses on the different compaction properties (i.e. MDD, OMC, CMC, etc.) as a function of the indicator test results of each material which produced these relatively high r^2-values. The author then decided to use these results for his PhD in Civil Engineering. The PhD thesis [1] was submitted in 1991 and the first paper[2] on these PhD results was published in the July /August version of the Journal of Transport Engineering, ASCE in 1994. The **DENSITY** prediction models were subsequently developed from these PhD test results. Since then the original **DENSITY** models were further refined so that both untreated and treated materials could be evaluated with the **DENSITY** software models. Today the **DENSITY** software models make provision for the evaluation of untreated materials, bitumen-treated materials and OPC mixes.

In South Africa the road alignment, soil investigation along the proposed route, pavement design, construction specifications and quality control of a road construction project itself are usually executed by consulting engineers appointed by the client for the project. The construction contract is usually awarded to the contractor with the lowest “practically feasible” tender price compared to the consulting engineers’ design estimate. When the measured road building properties on site differ from the specified values in the contract specification it is usually contractually assumed by the client and consulting engineer that the error is the responsibility of the contractor and that it is his responsibility to correct the “construction mistake” to the satisfaction of the client’s site agent or else contractually prove that the problem is caused by some unknown factor allowing the contractor to be absolved from his contractual responsibility.

Sometimes an unexpected deviation in the site measured dry density results is due to a change of either the specified material quality or local site conditions (not originally identified during the original soil investigation) being experienced which is definitely not the contractual responsibility of the contractor because the alignment and structural design of the pavement as well the selection of suitable material sources are the responsibility of the appointed consulting engineer. The **DENSITY** program’s numerical prediction results of the compacted material can very effectively be used to identify these probable problem causes, to rectify the legal dispute between the contracting parties as rapidly and as effectively as possible. The fact that the consulting engineer is given a very limited time frame as well as a limited budget for soil investigation to find suitable road building materials along the proposed alignment of a new road is very often the cause of the fact that this “construction problem” was not identified during the design stage of the project. Clients will have to come to terms with the fact that there is no such thing as a risk-free design, and they must accept their fair share of that risk as well. If not, the cost of road construction will become intolerably high in future or otherwise road construction projects should only be awarded to contractors on a “design and construct” basis, where the contractor is also responsible for the road design itself and accepts the risk involved.

Although material specifications for road construction were derived from experience on other roads, their interpretation by inexperienced staff can cause serious problems as well. For example, although both the measured and **DENSITY** predicted results of a crushed stone base of a road showed that the material had been optimally compacted to plus 88%SD, the site agent advised the client to reject the crushed stone base because the measured grading curve was slightly outside the specified grading envelope on the coarse side of the specification. It should be emphasized that the grading curve only gives an indication of the dry density to which a granular material can be compacted. NOTHING MORE!!! Using the grading envelope grading values in the specification as input information in the **DENSITY** program, indicated that the crushed rock can be compacted to approximately 88% SD along the coarse side of the grading envelope, and only to approximately 86%SD along the fine side of the grading envelope. Surely, a higher level of compaction (%SD) should lead to higher layer stiffness and better performance of the road. Incidentally, the “initially rejected” road is still performing excellently after more than 10 years carrying a very high component of often very heavily overloaded heavy vehicles.

Road building materials can basically be divided into two broad categories, namely treated and untreated materials. Under the untreated material category, we understand road building materials which are used in their natural state without the addition of any additional material to the natural materials to affect the properties of the compacted material. Under the treated material category, we have two classes of materials, namely those materials of which the grading was mechanically improved either by mixing different natural materials together to improve the overall grading or the crushing of rock to have a specified grading curve, or otherwise natural gravel or crushed rock of a certain specified grading curve to which either a cementitious (i.e. Road lime, Portland Blast Furnace Cement (PBFC) or OPC) or bituminous binder has been added.

Because the material grading curve (i.e. particle size distribution) after compaction, and other indicator test ~~values~~ results such the Bulk Relative Density (BRD) and Apparent Relative Density (ARD) values of the coarse and fine fractions of the material at a particular spot, influences where the in situ density was determined by either the sand replacement test or the nuclear density gauge, all the other compaction related properties of the compacted material, namely the optimum moisture content (OMC) and the maximum dry density (MDD in terms of kg/m^3 or space occupied by solid particles (%SD)), as well as the critical moisture content (CMC)(i.e. the moisture content at which the CBR peaks for a particular material grading curve), it should be very clear that the quality of the compacted material (in a particular layer) in a specific section which is treated as a construction lot for quality control purposes should be as uniform as possible (i.e. similar grading and OMC). If this uniform quality aspect of the material is ignored by the contractor, it will lead to a variation in density levels being achieved with certain sections in the lot being optimally compacted (at the right specified OMC for the grading) and other spots under-compacted, because the specified OMC is either too low or too high for the particular grading at that particular spot.

Up till recently the specified dry density in many countries is still specified in terms of MDD mod AASHTO (i.e. with the specified amount of mechanical applied compaction effort) for most layers. Because the maximum particle size in the mod AASHTO compaction test is 20 mm (because of the compaction mould size in the laboratory). Therefore, all material gradings containing larger particles than 20 mm will most likely be under-compacted (i.e. not have a tight particle matrix) although the material was compacted with the specified mod AASHTO compaction effort. Because it was also wrongly assumed in the past that the highest dry density that could be achieved was 100 % mod AASHTO, the maximum dry density specified for field compaction of crushed stone base layers was set at 98 % mod AASHTO. However, with the high tyre contact pressure of heavy vehicles these days the in-situ layer will rut (due to further densification) until full particle interlock is achieved for the material grading curve. To prevent subsequent rutting of road construction layers taking place, it is therefore absolutely necessary that all pavement layers be compacted to **refusal dry density** in the field (i.e. the dry density at which the application of further compaction energy does not increase the dry density (in terms of space occupied by particle solids). The specified mod AASHTO density will usually be less than 98% mod AASHTO for materials with a maximum particle size of 20 mm or smaller. The higher compaction levels achieved in the field will not only ensure that road does not unnecessarily deform, but should lead to a substantial increase in life expectancy of the pavement due to increased bearing strength. Because the extra compaction effort applied by the contractor to reach refusal dry density costs time and money, it is only fair that he be reimbursed for these costs. The extra construction cost should be more than offset by the better performance of the road and reduced maintenance cost of the road in the future.

For fill and in situ subgrade the specified dry density is usually set at 90% mod AASHTO, because of the inherent variability of the quality and moisture content of the in-situ material. If the pavement structure has a limited thickness and the fill or sub-grade is constructed over a swelling clay area, it is very important the in situ moisture content of the swelling clay is at such a moisture content level that it is more or less fixed, so that the in situ material will not shrink or swell during the life of the road, in order to prevent unnecessary deformation of the road pavement during the future. Because the fill or sub-grade may also be constructed over saturated soil areas of substantial thickness it is important that a fill overburden equivalent to the expected pavement load should be constructed over the road alignment in the saturated soil area and this overburden should be left in place until such time that the settlement of the overburden has stopped. Once the overburden does not settle significantly anymore the overburden may be removed and the subsequent selected sub-grade, sub-base, base and surfacing layers be constructed.

Examples of compaction problems solved with the DENSITY software

Problems with untreated materials

Problem 1

A contractor could not achieve the specified density level on a base layer on a certain road section. The contractor kept on applying more compaction energy in the form of more roller passes initially in the hope that this would solve the problem. However, this did not happen.

Usually in South Africa both the client and design engineer contractually assume that the design is perfect and do not want to get involved in solving a construction problem which is seen as the contractual responsibility of the contractor. This normally leads to the declaring of a construction dispute in which the contractor must then prove that the problem is not his responsibility, or rectify the problem. When the road designer in this case eventually entered the picture, he could not solve or explain the cause of the problem either. When the indicator test results of the particular layer with the measured low density results were entered into the **DENSITY** software, it predicted that the material should be able to achieve the specified density criteria. To verify this, several samples of the “problem” material were compacted on the vibratory compaction table in a single layer. The vibratory table compaction results confirmed that the quality of the material being compacted was not the cause of the compaction problem. If the material being compacted is not the cause of the problem in the compacted layer, the cause of the problem must be deeper down in the pavement structure due the situation below the problem layer. It turned out that there was a layer of collapsing sand below the road section which had not been identified by the original soil survey.

Problem 2

In the construction in South Africa of a main provincial road the specified dry density of 88%AD for a crushed stone base could not be achieved. However, it was impossible to hammer a Dynamic Cone Penetrometer (DCP) into the compacted layer. When the indicator test results of the crushed stone were entered into the **DENSITY** software it predicted that the layer could be compacted to 88%BD but only to 84%AD because of the porosity of the crushed rock used in the construction of the base layer. The layer was then accepted, and the road is still performing fine. It should be emphasized that there is no way in which intra-particle pores inside the porous aggregate can be filled with particle solids.

Problem 3

A contractor was contractually blamed for the construction problem with a calcrete base layer. When the indicator test results of the sand replacement density test holes were used in the **DENSITY** program as input information, it turned out that the material had been optimally compacted for the in situ grading at these points. The calcrete material from the specified source had degraded during the compaction of the layer on the actual site. This was therefore not the contractor's responsibility as he had used the specified calcrete source. It is also of utmost importance that especially calcrete types of material, must be used on site to the same depth as what was tested during the evaluation of the borrow pit source. At a distance it may look the same (to the naked eye) in depth, but it will usually not be of the same quality and could be "pre-calcrete" deeper down.

Problem 4

The base specification of a road specified that the natural granular base had specified that to be compacted to at least 98% mod AASHTO (usually specified for natural gravel base construction). This density level was easily achieved during construction. However, in the maintenance period of the contract the natural gravel base started rutting. The contractor and subcontractor, who had crushed the natural gravel used for the construction of the base, were contractually blamed for the problem by the client and engineer. However, when the material's indicator test values of the field density testing points of the natural gravel base were used as input information in the **DENSITY** software program, the program predicted that the base material could have been compacted to a substantial higher density in terms of %SD than the specified density of 98% mod AASHTO. The cause of the problem therefore contractually lay with the design engineer who had specified 98% mod AASHTO.

Problems with cement treated materials

Problem 5

A contractor had problems with the construction of a cement stabilised sub-base layer which he could not achieve the specified density level during a very hot period of the year. Using the **DENSITY** program, it showed that the material should be able to meet the required density. Samples of the cemented material were then compacted over two-hour period in 30 minute intervals after the mixing in of the cement while the samples of the cement treated material were left in plastic bags exposed to the sun while recording the temperature of the samples at the time of compaction. These cement treated samples were then compacted on the vibratory compaction table. It turned out that the specified density could be achieved with those samples which were compacted immediately after mixing in the cement, but not with those samples which had undergone initial set because the sample temperature rose to above 30ºC (initial set temperature) even though the specification allowed an 8-hour construction period for the stabilised layer. To overcome his contractual predicament the contractor changed his construction sequence of the stabilised layer to the coolest period of the day (i.e. night) in order to avoid the high daily temperatures and during the construction and no further problems were experienced with the compaction of the stabilized layer.

Problems with bitumen treated materials

Problem 6

The surfacing contractor was blamed for the fact that the compacted premix surfacing had fatted up during construction. The contractor had been instructed to compact the surfacing to a bulk density of 97%AD (Rice) density (where all inter-particle and intra-particle voids are saturated with water). This BD limit was chosen to theoretically allow for 3 % air voids when compacted to maximum bulk density so that the mix would not become fatty. During the contract itself the measured Marshall Bulk Densities (BD) (as measured by weighing the uncoated Marshall briquettes in water to determine the “bulk” volume of the samples) as well as the apparent density (AD) (Rice) of the Marshall briquettes, the mix seemed in line with the quality control expectations. However, the premix surfacing soon became fatty and the contractor was blamed for over-rolling (applying too much compaction effort).

When the indicator test result information of the asphalt different slabs was entered into the **DENSITY** software program, the reason for the fattening up of the premix layer became apparent. The aggregate used for the manufacture of the asphalt mix was crushed porous basalt with about 3% intra-particle voids (i.e. voids inside the aggregate particles which can be filled with water when submerged in water under vacuum). During the determination of the bulk volume of the Marshall briquettes the samples were not coated with wax or plastic because it was assumed that the weighing of the submerged briquettes was so rapid that neither the inter-particle voids nor the intra-particle voids in the submerged briquettes, would be filled with water during this rapid weighing process. The AD (Rice) was measured in the usual manner by determining the briquette volumes under vacuum (results in Figure 1).

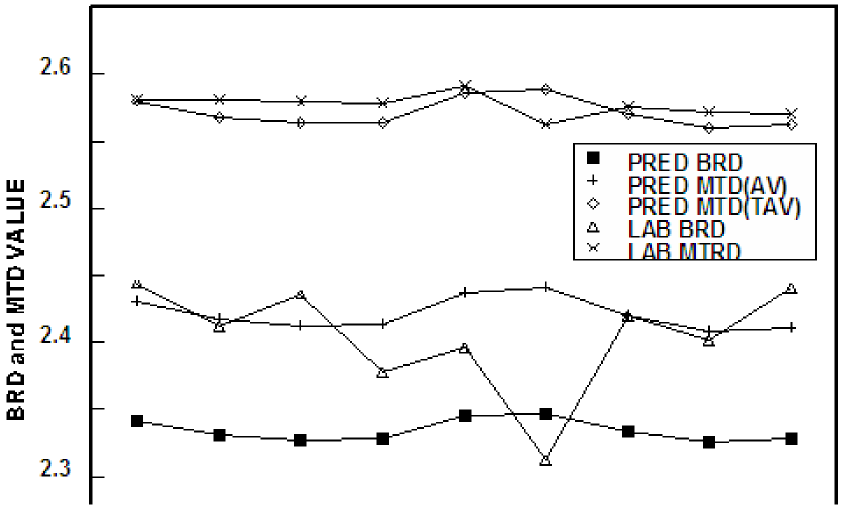


Figure 1- Comparison of DENSITY predictions with the laboratory determined values

The fact that the **DENSITY** predicted Maximum Theoretical Density (MTD(TAV) (i.e. with both the inter-particle and intra-particle voids theoretically filled with water) and LAB Maximum Theoretical Rice Density (MTRD (Rice)) agree, and the predicted MTD(AV)(i.e. only inter-particle air voids theoretically saturated with water) agreeing with the LAB BRD most of the time with one another while the **DENSITY** predicted BRD values of the different slabs evaluated were lower than the laboratory measured BRD values of the Marshall briquettes most of the time indicated that the measured Marshall BRD densities in the control laboratory were wrong, leading to the wrong instruction being given by the site engineer to the contractor to apply more compaction energy. The fact that predicted MTD(TAV) (i.e. with both the inter-particle voids and intra-particle voids theoretically filled with water) agrees with measured LAB MTRD (Rice) showed that the **DENSITY** predictions are accurate and reliable.

This was the very first “problem situation” of bitumen treated material that was investigated and solved with **DENSITY**.

Problem 7

A premix surfacing using crushed chrome waste as aggregate source became fatty, when using the normal binder ratio of approximately 4.5% by mass to the mix. When entering the grading, ARD and BRD of the coarse and fine fractions of the mix into the **DENSITY** software program it became clear why the premix became fatty. For most aggregate sources used for the manufacture of premix the bulk relative density (BRD) is in the order of 2.650. However, the BRD of chrome is substantially higher than 2.650. The standard amount of specified binder content of 4.5% (by mass) will be substantially more in terms of volume because of the higher BRD (i.e.4.002) of the chrome aggregate. Because the **DENSITY** models are based on volumetric properties rather than mass properties, the required amount of binder by volume is corrected by using the factor (2.650/BRD_{actual}) (of the mix) (see Tables 1 to 3 in Appendix).

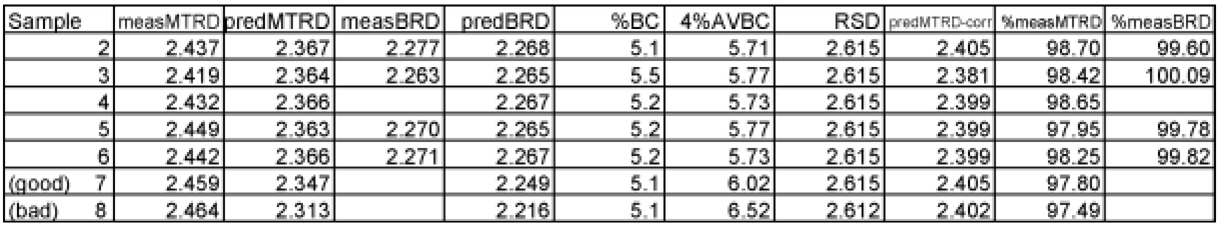
Problem 8

A paving contractor was blamed for the failure of premix surfacing where the supplied bitumen binder used for the construction mix that had been kept at an elevated storage temperature for an extended period (of more than one month) in heated storage tanks at the premix plant before actually being used it for the manufacture of premix. From the collected Marshall briquette information used in the **DENSITY** program it became clear that the R&B value had changed substantially from the original R&B value just after production at the oil refinery during the extended storage period at an elevated temperature (in order to keep the binder flowable). It is therefore very important that the asphalt construction mix be compared with the design mix properties before starting with the actual paving in order to ensure that the R&B value of produced premix material agrees with the R&B value of the premix design.

Comparison of the measured and predicted **DENSITY** results of the recovered binder clearly show that the binder was probably burnt at some stage both on the good and bad areas. The saving grace of the good paved areas is the high content of volatiles present in the recovered binder, which comes from the penetration and tack coats, which may have been over-applied.

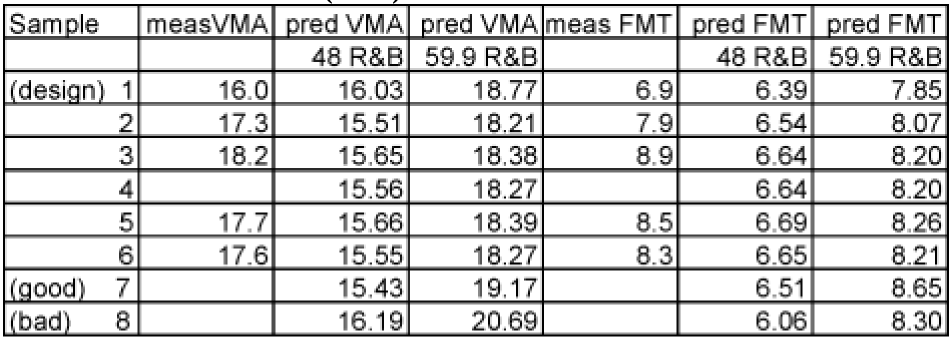
The higher measured VMAs than the **DENSITY** predicted VMAs (for 59.9 R&B) and lower BRDs confirm that the binder was substantially stiffer during construction than originally anticipated, leading to the aggregate particles being forced further apart due to a thicker binder film thickness (see Table 2).

Table 1: Comparison of the measured and predicted values of the MTRD and BRD for the same grading curves



Sample	measMTRD	predMTRD	measBRD	predBRD	%BC	4%AVBC	RSD	predMTRD-corr	%measMTRD	%measBRD
2	2.437	2.367	2.277	2.268	5.1	5.71	2.615	2.405	98.70	99.60
3	2.419	2.364	2.263	2.265	5.5	5.77	2.615	2.381	98.42	100.09
4	2.432	2.366		2.267	5.2	5.73	2.615	2.399	98.65	
5	2.449	2.363	2.270	2.265	5.2	5.77	2.615	2.399	97.95	99.78
6	2.442	2.366	2.271	2.267	5.2	5.73	2.615	2.399	98.25	99.82
(good) 7	2.459	2.347		2.249	5.1	6.02	2.615	2.405	97.80	
(bad) 8	2.464	2.313		2.216	5.1	6.52	2.612	2.402	97.49	

Table 2: Measured and DENSITY predicted Voids in Mineral Aggregate (VMA) and binder film thickness (FMT) values for the different mixes



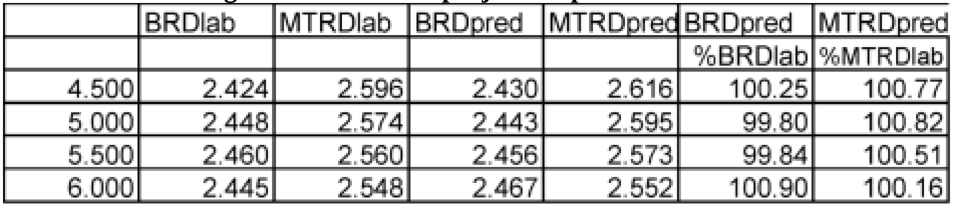
Sample	measVMA	pred VMA	pred VMA	meas FMT	pred FMT	pred FMT
		48 R&B	59.9 R&B		48 R&B	59.9 R&B
(design) 1	16.0	16.03	18.77	6.9	6.39	7.85
2	17.3	15.51	18.21	7.9	6.54	8.07
3	18.2	15.65	18.38	8.9	6.64	8.20
4		15.56	18.27		6.64	8.20
5	17.7	15.66	18.39	8.5	6.69	8.26
6	17.6	15.55	18.27	8.3	6.65	8.21
(good) 7		15.43	19.17		6.51	8.65
(bad) 8		16.19	20.69		6.06	8.30

The oil refinery testing certificate indicated that the binder properties were determined on 9 March 2001). The weight bill of the tanker delivering the binder from Durban to East London is marked 13 March 2001, but the site results are for 19 April 2001. This means that the binder had been kept at an elevated temperature at the premix plant for more than a month before use. The weight bills of the trucks delivering the asphalt mix to site show a maximum temperature of 165 °C, which is not high enough to burn the binder during the manufacture or laying of the premix. The conclusion reached at that stage (2003) was that the most likely cause for the poor performance of the asphalt is the fact that the bitumen binder had been stored at an elevated temperature for such a long period before being used. This conclusion was highly disputed by the bitumen binder supplier at that stage.

Problem 9

In 2004 when this analysis was done with **DENSITY**, the bitumen industry in general categorically stated that their product was very stable and that any change in binder properties were due to mismanagement during the construction process such as burning of the binder. In this example the paving contractor could not come right with the mix of the contract. Although the asphalt paving seemed acceptable initially (just after construction), the asphalt paving started cracking shortly afterwards during the so-called "maintenance period" of the road. The contractor was contractually blamed for the “mistake” and because he could not prove that it was not his problem, he redid the “bad” work several times with the same devastating result each time. The consulting engineers and client of the project could not explain this phenomenon either. Subsequently the client appointed some other civil engineering consultants to try and find the cause of the problem, but they could not explain the cause of the problem either. The contractor then requested the ~~first~~ author to evaluate the construction results with the **DENSITY** prediction software (see Tables 3 to 5).

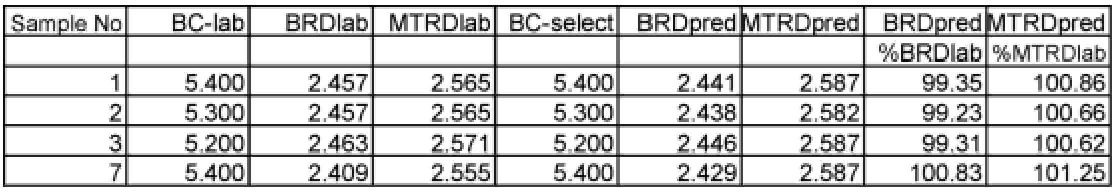
Table 3: Laboratory and DENSITY predicted values from the premix plant of the BRD and MTRD values for the design-mix of the road project for particular binder contents



	BRDlab	MTRDlab	BRDpred	MTRDpred	BRDpred	MTRDpred
					%BRDlab	%MTRDlab
4.500	2.424	2.596	2.430	2.616	100.25	100.77
5.000	2.448	2.574	2.443	2.595	99.80	100.82
5.500	2.460	2.560	2.456	2.573	99.84	100.51
6.000	2.445	2.548	2.467	2.552	100.90	100.16

The plant design mix was also compared with **DENSITY** predictions. As the grading information was only available for the 19, 4.75, 0.600 and 0.075 mm sieves, the numerical values for the other missing standard sieves were determined by straight line interpolation in order to do the **DENSITY** analysis. The sample numbers in Table 4 apply to the information of the first row of the as compacted data of the first sheet in the report by the special consulting engineers appointed by the client to investigate the problem.

Table 4: Summary of the comparison between the BRD and MTRD values of randomly select samples of the second premix plant used on project and the DENSITY predictions of the BRD and MTRD for the same binder content

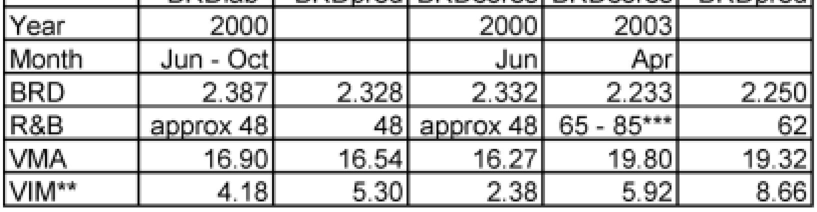


Sample No	BC-lab	BRDlab	MTRDlab	BC-select	BRDpred	MTRDpred	BRDpred	MTRDpred
							%BRDlab	%MTRDlab
1	5.400	2.457	2.565	5.400	2.441	2.587	99.35	100.86
2	5.300	2.457	2.565	5.300	2.438	2.582	99.23	100.66
3	5.200	2.463	2.571	5.200	2.446	2.587	99.31	100.62
7	5.400	2.409	2.555	5.400	2.429	2.587	100.83	101.25

Once again, the comparison between the laboratory and the **DENSITY** predicted values is excellent for an R&B value of 49 (i.e. R&B value at the time of construction) in the prediction model. This confirms that the R&B value of the binder was very similar to that of the supplied binder after manufacture of the asphalt mix, ruling out the hardening of the binder during the actual mixing and paving processes.

To show what the effect of such a change of the R&B value during manufacture or placing would have been on the properties of the asphalt the results of Sample 7 are also shown for an R&B value of 62. Note: if the binder content was kept at 5.4 per cent, the MTRD would be 2.576, like that of the binder for an R&B value of 49 (i.e. 2.575). However, the BRD value would change from 2.429 to 2.362 and the voids in mineral aggregate (VMA) value changes from 17.50% to 19.78%, due to the loss of volatiles from the binder causing shrinking cracks.

Table 5: Comparison of average properties of first premix plant used on project of compacted cores at different dates and measured and predicted properties for R&B values of 48 and 62



	BRDlab*	BRDpred	BRDcores	BRDcores	BRDpred
Year	2000		2000	2003	
Month	Jun - Oct		Jun	Apr	
BRD	2.387	2.328	2.332	2.233	2.250
R&B	approx 48	48	approx 48	65 - 85***	62
VMA	16.90	16.54	16.27	19.80	19.32
VIM**	4.18	5.30	2.38	5.92	8.66

*	BRDlab values are usually somewhat higher than BRDpred because the inter-particle void space is partially filled with water when weighing sample in water
**	Increase in VIM under traffic is abnormal. If LBPC formulation was correct the VIM would have decreased under traffic
***	Exceptionally high R&B values probably due to super fines content in the recovered binder

Conclusions at the end of the DENSITY investigation (2004) of this particular problem

When using the **DENSITY** program for bituminous treated material, provision is made for the variation of the stiffness of different binder types, because the binder stiffness influences the binder layer thickness around the aggregate particles, which directly influences the inter- particle void content, the BRD of the mix as well as all the other properties such as the Rice density (i.e. MTD (taking account of both inter-particle voids and intra-particle voids) and the VMA. Fortunately, the asphalt premix supplier had recorded the Ring and Ball temperature (R&B) during the manufacturing of the premix and the paving contractor had done the same at different stages of the paving process.

Based on the information that was made available and the volumetric analyses the following conclusions were reached:

- The same type of binder was used for the mix design as was used for the manufacturing of the asphalt (i.e. R&B = 48 degrees centigrade).
- The binder R&B value was not significantly altered during the manufacturing and the paving operations (i.e. R&B = approximately 48 degrees centigrade).
- Based on the outcome of the volumetric analyses of both projects it is concluded that the site supervision for the original work done by the engineer is of the same standard as for the repair work done by the engineer for the special investigation.
- The rapid aging of the binder probably did not take place during either the mixing or paving processes on this project. It probably took place after completion of the construction process but during the contractual maintenance period of the project.
- The problem is therefore not due to bad manufacturing, construction or supervision practices but is bitumen binder related which is beyond the control of any of the three parties involved and therefore could not have been foreseen by them (latent defect of the binder).
- The binder that was formulated and produced was probably not durable enough to perform successfully under the environmental conditions generally experienced in the particular province and therefore it was the author’s opinion that the binder formulator or binder supplier be held contractually responsible for this problem.
- The premature aging of the binder was prone to the loss of adhesive and cohesive properties, resulting in premature cracking (fatigue cracking, thermal expansion cracking and crack propagation), as well as the ravelling of the asphalt only after construction.
- With normal binder the Voids in Mix (VIM) decreases under traffic but in this particular case the VIM increases with brittleness features at low temperatures.

Using the measured BRD and ARD values of the aggregate used and other measured test results from the Marshall briquettes from before, during and after the construction process including the special investigation as input information in the **DENSITY** program, it became apparent that the binder stiffness had changed after the actual construction of the premix surfacing (but inside the contractual “maintenance period”) because of the loss of volatiles from the binder. Although the loss of these volatiles did not take place during the actual construction process, the change in the binder properties occurred within the contractual maintenance period of the road project and was therefore originally seen as the contractual responsibility of the contractor.

Further independent laboratory testing on the binder by the road binder section of the Built Environment Division at the Council for Scientific and Industrial Research (CSIR) however proved the probable **DENSITY** predictions as the true cause beyond any doubt.

Problem 10

The paving contractor of the construction of a Bitumen Treated Base (BTB) of 26.5 mm max particle size was contractually blamed for the fattening up of the compacted base layer during construction. However, when the procured Marshall briquette results, produced for quality assurance purposes of the project, were used as numerical input information into the **DENSITY** program, it became clear that the binder stiffness, as measured by the R&B temperature value of the binder, varied from the design mix R&B value of 52º C. When the predicted R&B temperature of the supplied bitumen changed to 48ºC in the **DENSITY** program, the predicted DBD became fatty because of a thicker than required binder layer for the in situ binder stiffness and specified binder content.

The **DENSITY** program also showed that if the client wanted to use the specified binder with the wide tolerance specification for the R&B value from 52 to 48, the maximum particle size had to be reduced from 28.0 mm to 20.0 mm in order for the large aggregate mix base not to fat up during compaction if the R&B value changes from 52 to 48 for a fixed binder content (see Tables 4 and 6 in Appendix).

Since these "unexpected" negative results with the "so-called stable" bitumen binder properties the binder supply companies in South Africa have stated categorically that they do not contractually accept any responsibility for the variability of their products.

II. Conclusion

It is clear from these limited numbers of actual examples that none of these compaction problems (even High Modulus Asphalt (EME) mixes (no problem with mix)(see Table 7 and 8 in Appendix) would have been solved with standard testing methods or continued application of compaction energy. Therefore, the best manner to solve an unknown compaction problem, is first to analyse the laboratory measured results with the **DENSITY** program. If the **DENSITY** predictions for the same indicator test values agree with laboratory measured values, then the problem is probably deeper down in the pavement structure itself (e.g. Problem 1). However, if the **DENSITY** predictions for the same indicator test values differ from laboratory measured values, then the problem is probably in the particular layer itself.

Further refined laboratory testing on the problem material may be necessary to contractually convince the parties involved if they are not fully convinced of the **DENSITY** prediction results.

Compaction problems experienced in other parts of the world have also been solved with the **DENSITY** program. For example, problems with bituminous mixes have been clarified in Nigeria, Bangladesh, Europe and the USA. Other countries where the compaction problem in treated and untreated material could be explained with the **DENSITY** program were China and Sri Lanka.

Acknowledgement

The author would like to thank Mr NJJ Jooste for his very valuable contribution in writing this paper. The author would also like to acknowledge God, the Creator of the universe, who gave him the insight to develop these models.

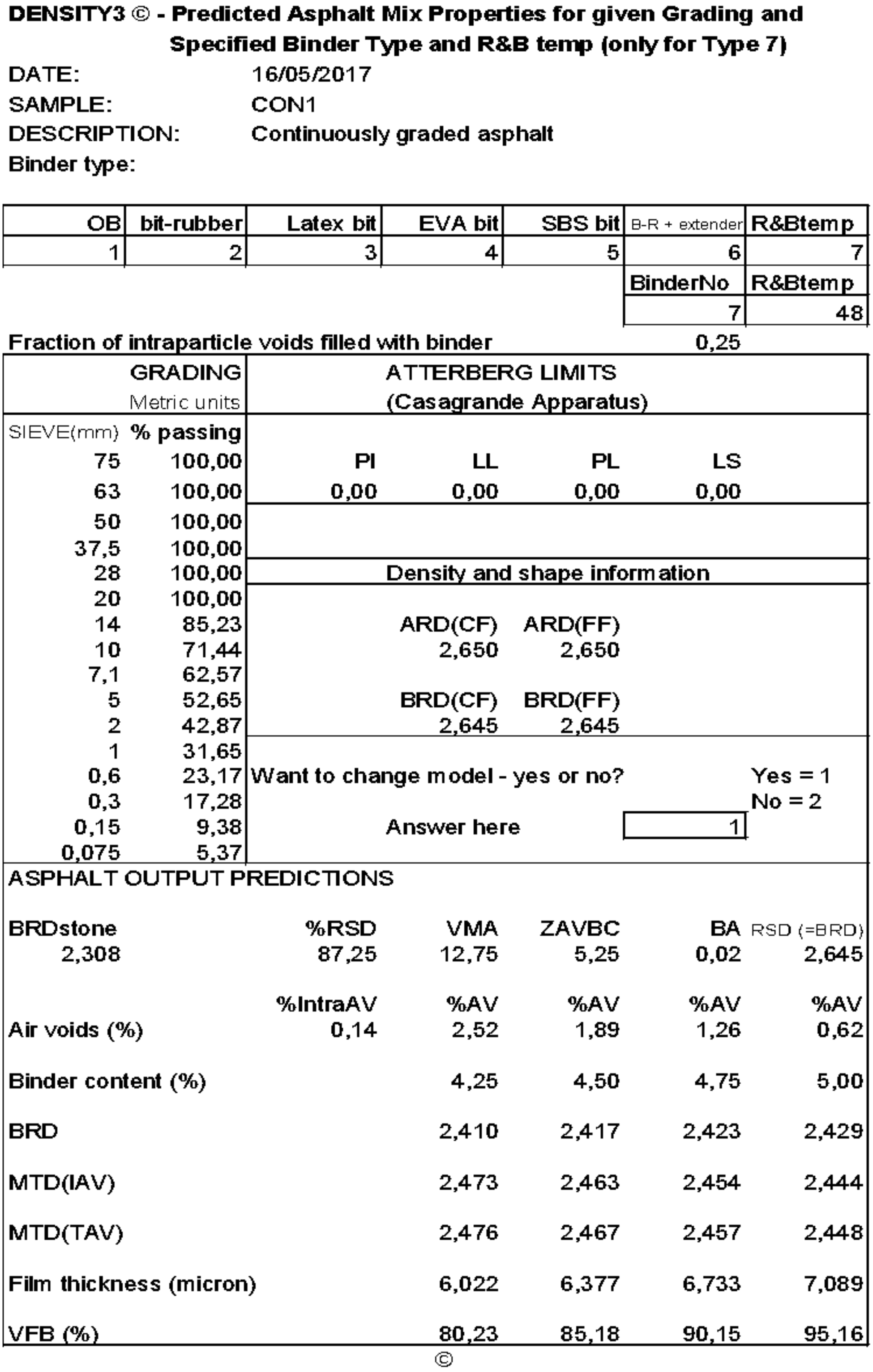
Bibliography

[1]. Semmelink C.J. 1991. The effect of material properties on the compactability of some untreated roadbuilding materials PhD Thesis.

[2]. Semmelink C.J. and Visser A.T. 1994. Effect of material properties on compactability and bearing capacity. Journal of Transportation Engineering, ASCE, Vol.120, No.4, Jul/Aug 1994. 20p.

APPENDIX

The DENSITY predictions for the same asphalt mix without correcting the mass of binder for the change in the true BRD and ARD of the aggregate.



DENSITY3 © - Predicted Asphalt Mix Properties for given Grading and Specified Binder Type and R&B temp (only for Type 7)

DATE: 16/05/2017
SAMPLE: CON1
DESCRIPTION: Continuously graded asphalt
Binder type:

OB	bit-rubber	Latex bit	EVA bit	SBS bit	B-R + extender	R&Btemp
1	2	3	4	5	6	7

BinderNo	R&Btemp
7	48

Fraction of intraparticle voids filled with binder 0,25

GRADING Metric units	
SIEVE(mm)	% passing
75	100,00
63	100,00
50	100,00
37,5	100,00
28	100,00
20	100,00
14	85,23
10	71,44
7,1	62,57
5	52,65
2	42,87
1	31,65
0,6	23,17
0,3	17,28
0,15	9,38
0,075	5,37

ATTERBERG LIMITS
(Casagrande Apparatus)

PI	LL	PL	LS
0,00	0,00	0,00	0,00

Density and shape information

ARD(CF)	ARD(FF)
2,650	2,650

BRD(CF)	BRD(FF)
2,645	2,645

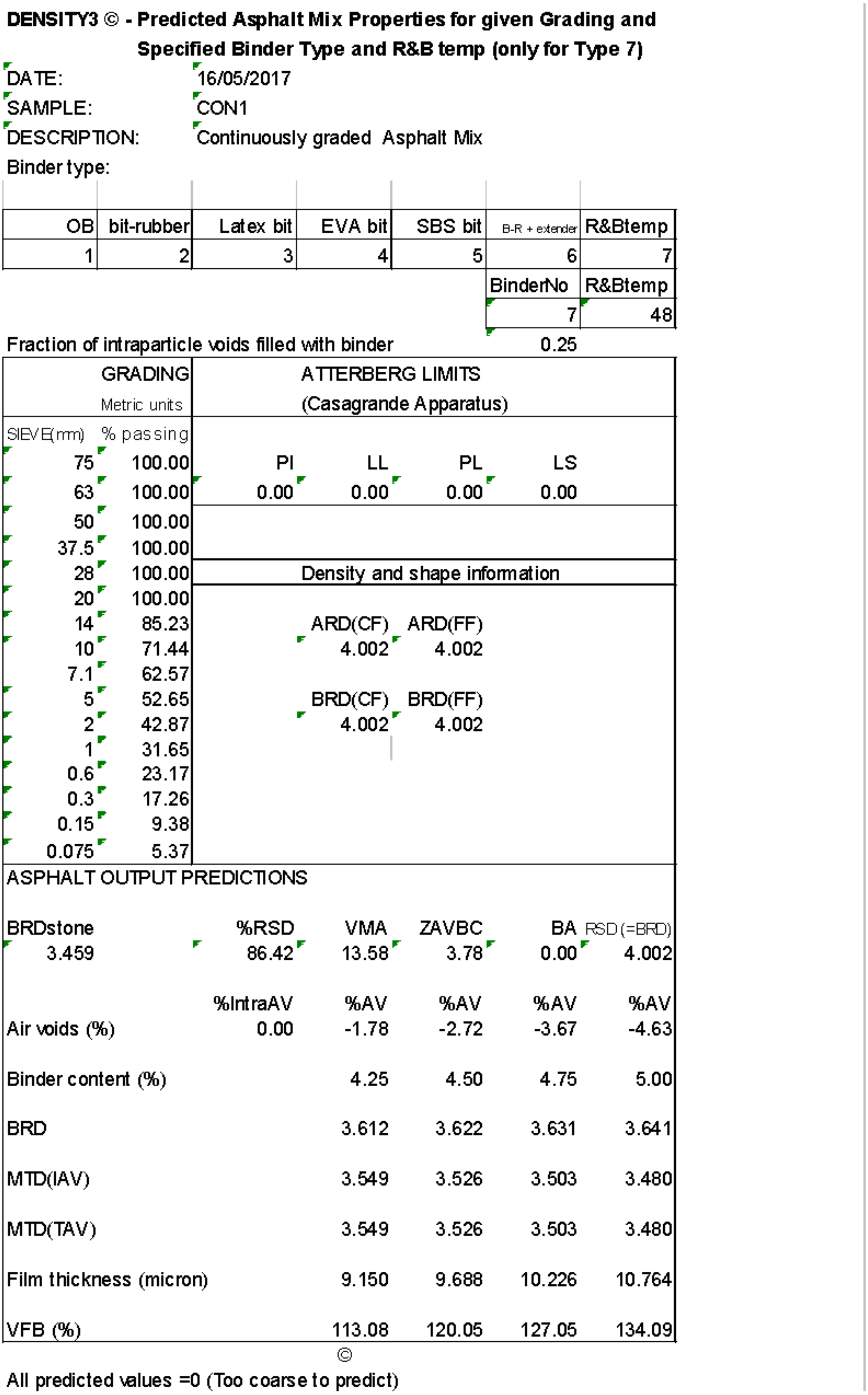
Want to change model - yes or no? Yes = 1
No = 2
Answer here 1

ASPHALT OUTPUT PREDICTIONS

BRDstone	%RSD	VMA	ZAVBC	BA	RSD (=BRD)
2,308	87,25	12,75	5,25	0,02	2,645

	%IntraAV	%AV	%AV	%AV	%AV
Air voids (%)	0,14	2,52	1,89	1,26	0,62
Binder content (%)		4,25	4,50	4,75	5,00
BRD		2,410	2,417	2,423	2,429
MTD(IAV)		2,473	2,463	2,454	2,444
MTD(TAV)		2,476	2,467	2,457	2,448
Film thickness (micron)		6,022	6,377	6,733	7,089
VFB (%)		80,23	85,18	90,15	95,16

©



DENSITY3 © - Predicted Asphalt Mix Properties for given Grading and Specified Binder Type and R&B temp (only for Type 7)

DATE:	16/05/2017
SAMPLE:	CON1
DESCRIPTION:	Continuously graded Asphalt Mix

Binder type:

OB	bit-rubber	Latex bit	EVA bit	SBS bit	B-R + extender	R&Btemp
1	2	3	4	5	6	7

BinderNo	R&Btemp
7	48

Fraction of intraparticle voids filled with binder 0.25

GRADING Metric units	
SIEVE(mm)	% passing
75	100.00
63	100.00
50	100.00
37.5	100.00
28	100.00
20	100.00
14	85.23
10	71.44
7.1	62.57
5	52.65
2	42.87
1	31.65
0.6	23.17
0.3	17.26
0.15	9.38
0.075	5.37

ATTERBERG LIMITS
(Casagrande Apparatus)

PI	LL	PL	LS
0.00	0.00	0.00	0.00

Density and shape information

ARD(CF)	ARD(FF)
4.002	4.002

BRD(CF)	BRD(FF)
4.002	4.002

ASPHALT OUTPUT PREDICTIONS

BRDstone	%RSD	VMA	ZAVBC	BA	RSD (=BRD)
3.459	86.42	13.58	3.78	0.00	4.002

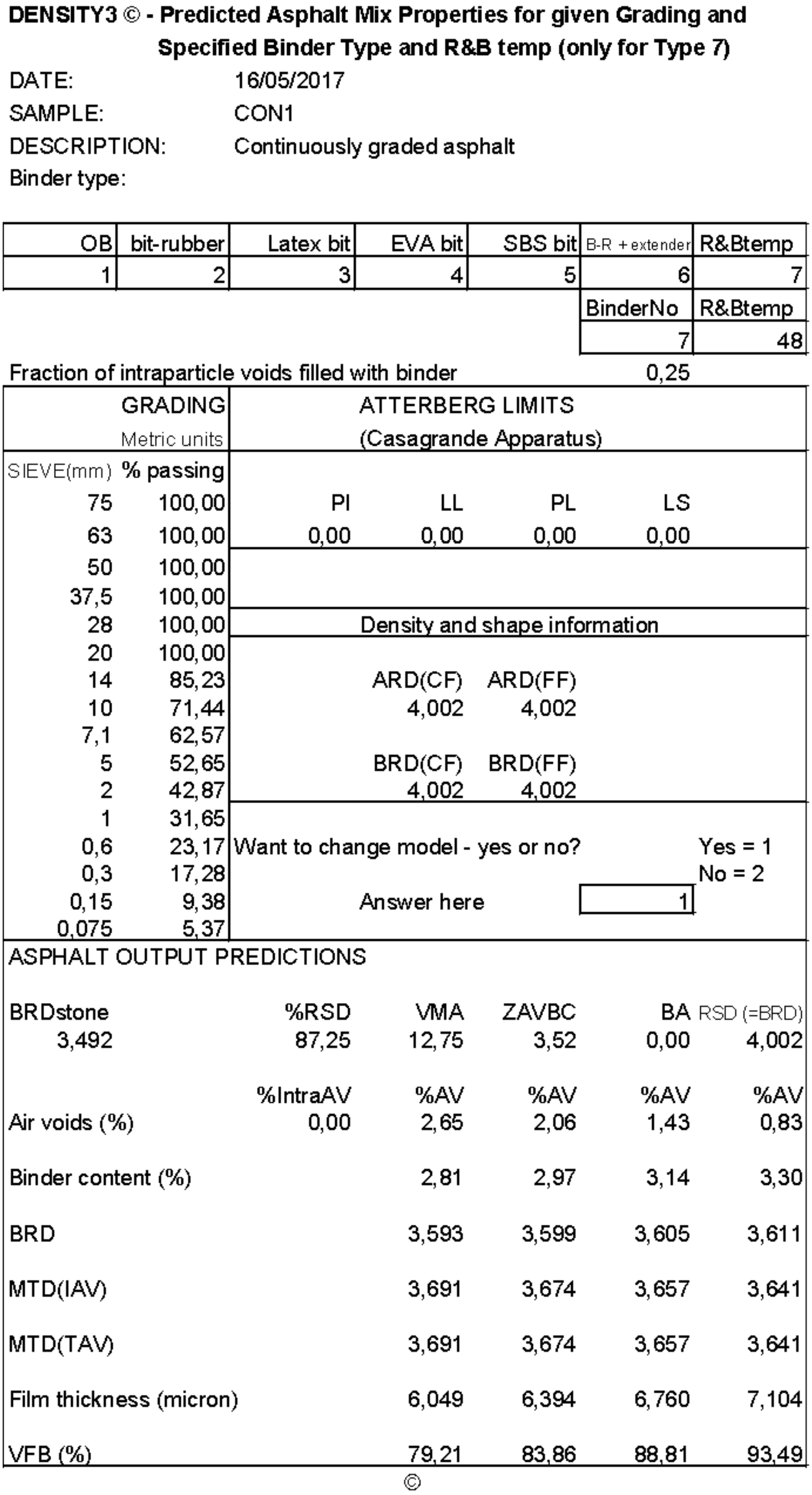
	%IntraAV	%AV	%AV	%AV	%AV
Air voids (%)	0.00	-1.78	-2.72	-3.67	-4.63
Binder content (%)		4.25	4.50	4.75	5.00
BRD		3.612	3.622	3.631	3.641
MTD(IAV)		3.549	3.526	3.503	3.480
MTD(TAV)		3.549	3.526	3.503	3.480
Film thickness (micron)		9.150	9.688	10.226	10.764
VFB (%)		113.08	120.05	127.05	134.09

©

All predicted values =0 (Too coarse to predict)

This shows the negative effect of the BRD value on the amount of binder if fixed as a percentage of the mass.

The DENSITY predictions for the same asphalt mix correcting the mass of binder on a volumetric base for the change in the true BRD and ARD values of the aggregate used.



DENSITY3 © - Predicted Asphalt Mix Properties for given Grading and Specified Binder Type and R&B temp (only for Type 7)

DATE:	16/05/2017
SAMPLE:	CON1
DESCRIPTION:	Continuously graded asphalt
Binder type:	

OB	bit-rubber	Latex bit	EVA bit	SBS bit	B-R + extender	R&Btemp
1	2	3	4	5	6	7

BinderNo	R&Btemp
7	48

Fraction of intraparticle voids filled with binder 0,25

GRADING
Metric units

SIEVE(mm)	% passing
75	100,00
63	100,00
50	100,00
37,5	100,00
28	100,00
20	100,00
14	85,23
10	71,44
7,1	62,57
5	52,65
2	42,87
1	31,65
0,6	23,17
0,3	17,28
0,15	9,38
0,075	5,37

ATTERBERG LIMITS
(Casagrande Apparatus)

PI	LL	PL	LS
0,00	0,00	0,00	0,00

Density and shape information

ARD(CF)	ARD(FF)
4,002	4,002

BRD(CF)	BRD(FF)
4,002	4,002

Want to change model - yes or no? Yes = 1
No = 2

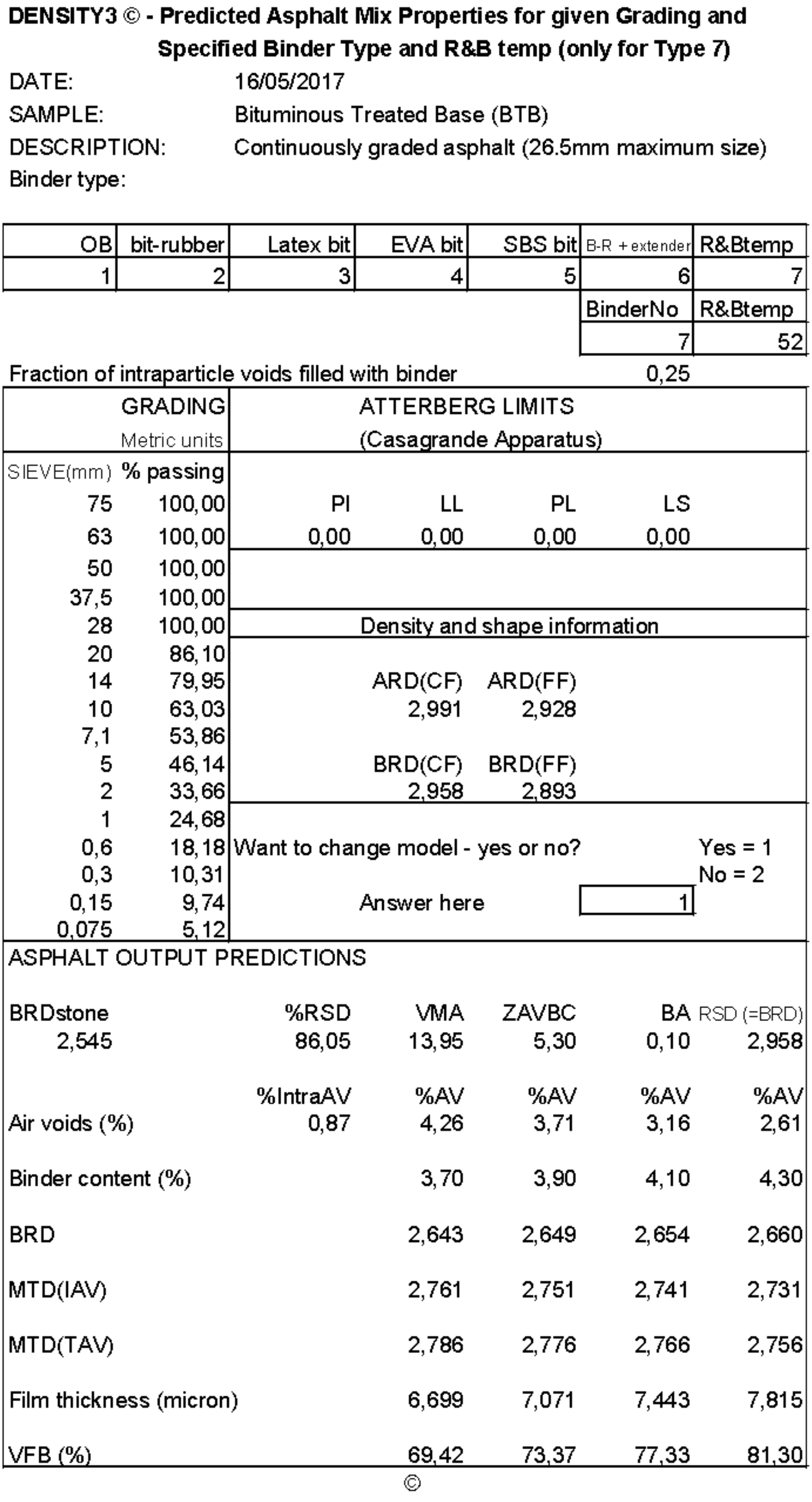
Answer here 1

ASPHALT OUTPUT PREDICTIONS

BRDstone	%RSD	VMA	ZAVBC	BA	RSD (=BRD)
3,492	87,25	12,75	3,52	0,00	4,002

	%IntraAV	%AV	%AV	%AV	%AV
Air voids (%)	0,00	2,65	2,06	1,43	0,83
Binder content (%)		2,81	2,97	3,14	3,30
BRD		3,593	3,599	3,605	3,611
MTD(IAV)		3,691	3,674	3,657	3,641
MTD(TAV)		3,691	3,674	3,657	3,641
Film thickness (micron)		6,049	6,394	6,760	7,104
VFB (%)		79,21	83,86	88,81	93,49

©



DENSITY3 © - Predicted Asphalt Mix Properties for given Grading and Specified Binder Type and R&B temp (only for Type 7)

DATE:	16/05/2017
SAMPLE:	Bituminous Treated Base (BTB)
DESCRIPTION:	Continuously graded asphalt (26.5mm maximum size)
Binder type:	

OB	bit-rubber	Latex bit	EVA bit	SBS bit	B-R + extender	R&Btemp
1	2	3	4	5	6	7

BinderNo	R&Btemp
7	52

Fraction of intraparticle voids filled with binder 0,25

GRADING Metric units	
SIEVE(mm)	% passing
75	100,00
63	100,00
50	100,00
37,5	100,00
28	100,00
20	86,10
14	79,95
10	63,03
7,1	53,86
5	46,14
2	33,66
1	24,68
0,6	18,18
0,3	10,31
0,15	9,74
0,075	5,12

ATTERBERG LIMITS
(Casagrande Apparatus)

PI	LL	PL	LS
0,00	0,00	0,00	0,00

Density and shape information

ARD(CF)	ARD(FF)
2,991	2,928

BRD(CF)	BRD(FF)
2,958	2,893

Want to change model - yes or no? Yes = 1
No = 2

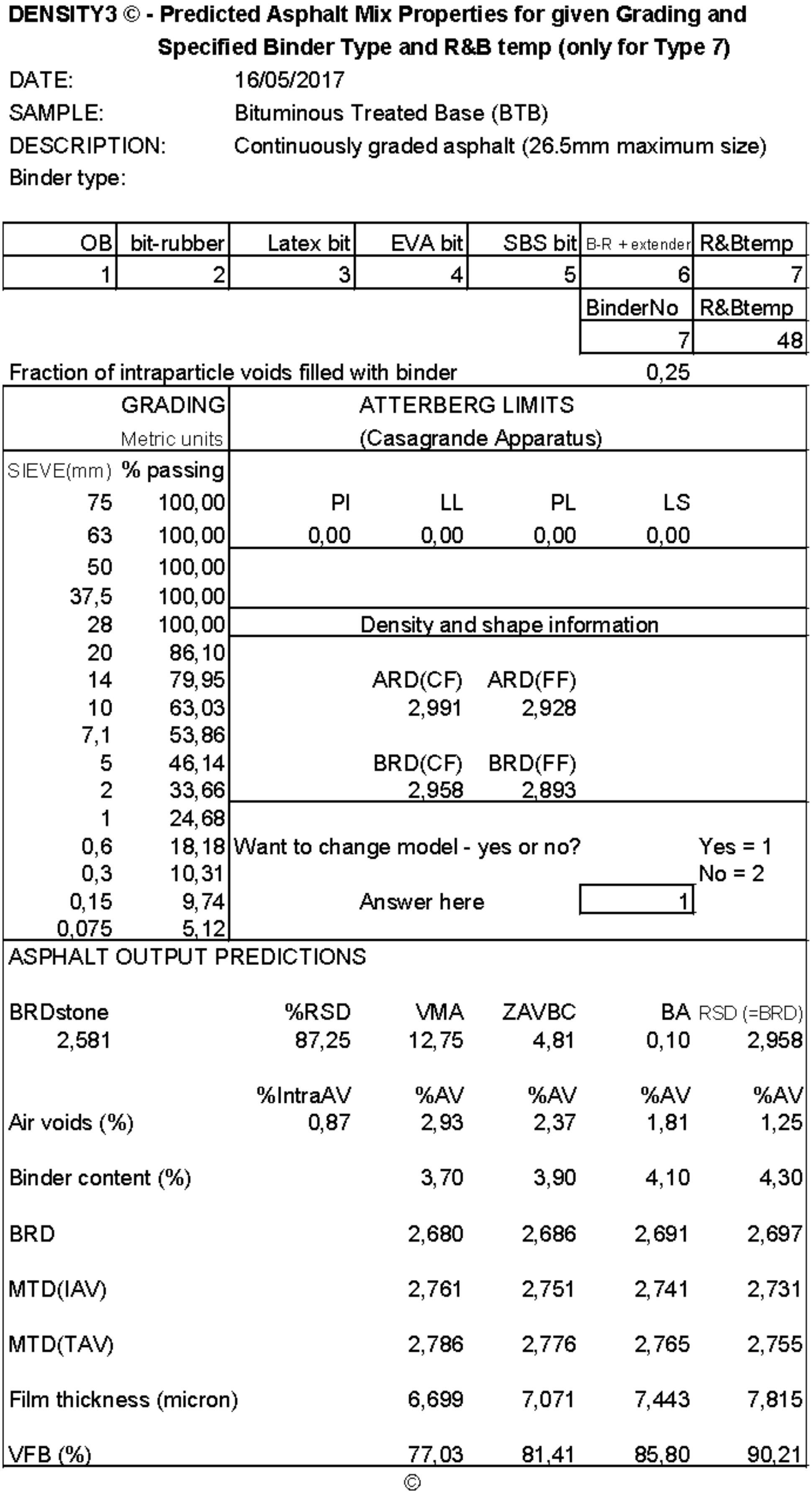
Answer here 1

ASPHALT OUTPUT PREDICTIONS

BRDstone	%RSD	VMA	ZAVBC	BA	RSD (=BRD)
2,545	86,05	13,95	5,30	0,10	2,958

	%IntraAV	%AV	%AV	%AV	%AV
Air voids (%)	0,87	4,26	3,71	3,16	2,61
Binder content (%)		3,70	3,90	4,10	4,30
BRD		2,643	2,649	2,654	2,660
MTD(IAV)		2,761	2,751	2,741	2,731
MTD(TAV)		2,786	2,776	2,766	2,756
Film thickness (micron)		6,699	7,071	7,443	7,815
VFB (%)		69,42	73,37	77,33	81,30

©



DENSITY3 © - Predicted Asphalt Mix Properties for given Grading and Specified Binder Type and R&B temp (only for Type 7)

DATE: 16/05/2017
SAMPLE: Bituminous Treated Base (BTB)
DESCRIPTION: Continuously graded asphalt (26.5mm maximum size)
Binder type:

OB	bit-rubber	Latex bit	EVA bit	SBS bit	B-R + extender	R&Btemp
1	2	3	4	5	6	7

BinderNo	R&Btemp
7	48

Fraction of intraparticle voids filled with binder 0,25

GRADING
Metric units

SIEVE(mm)	% passing
75	100,00
63	100,00
50	100,00
37,5	100,00
28	100,00
20	86,10
14	79,95
10	63,03
7,1	53,86
5	46,14
2	33,66
1	24,68
0,6	18,18
0,3	10,31
0,15	9,74
0,075	5,12

ATTERBERG LIMITS
(Casagrande Apparatus)

PI	LL	PL	LS
0,00	0,00	0,00	0,00

Density and shape information

ARD(CF)	ARD(FF)
2,991	2,928

BRD(CF)	BRD(FF)
2,958	2,893

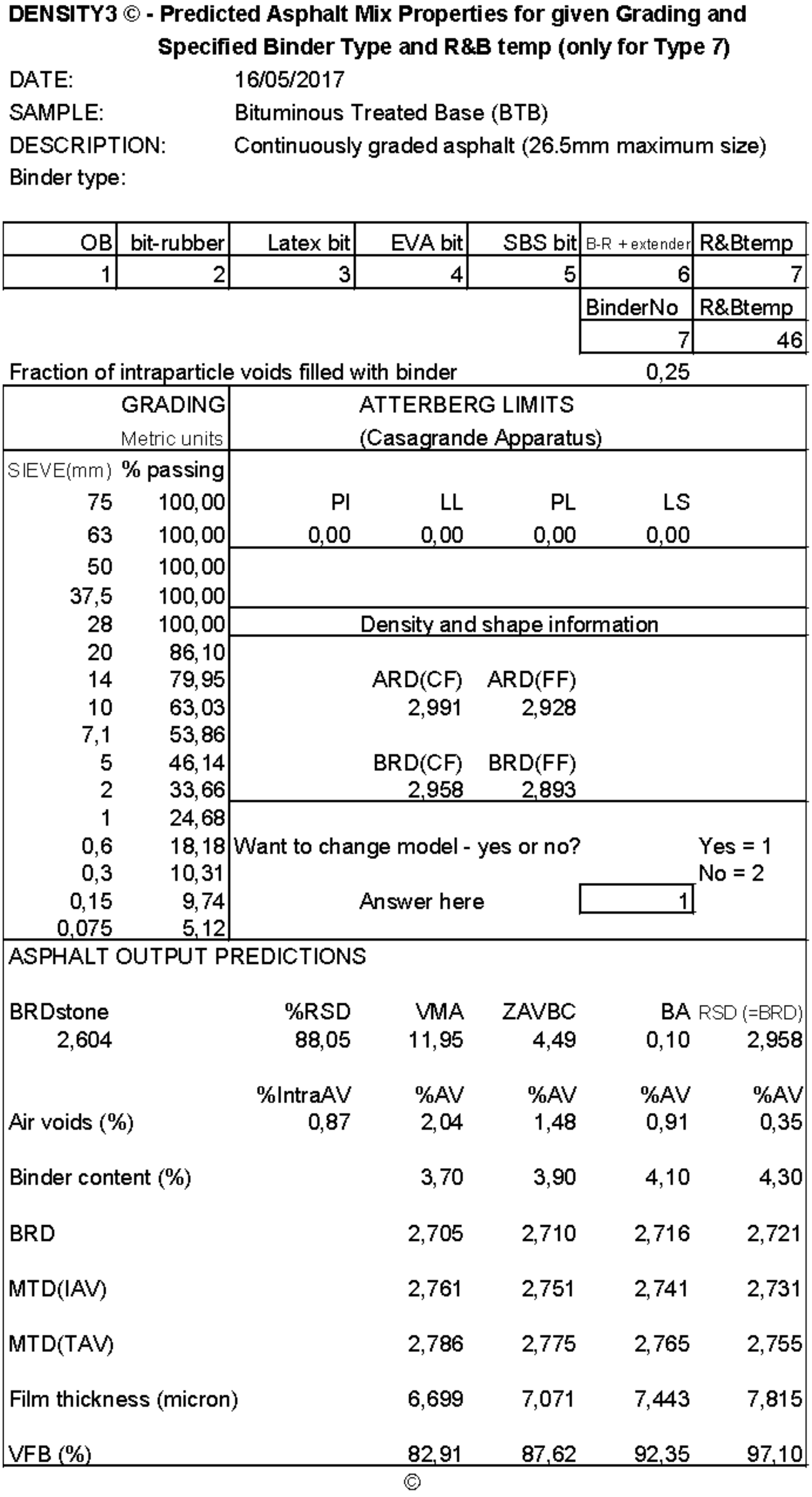
Want to change model - yes or no? Yes = 1
No = 2
Answer here 1

ASPHALT OUTPUT PREDICTIONS

BRDstone	%RSD	VMA	ZAVBC	BA	RSD (=BRD)
2,581	87,25	12,75	4,81	0,10	2,958

	%IntraAV	%AV	%AV	%AV	%AV
Air voids (%)	0,87	2,93	2,37	1,81	1,25
Binder content (%)		3,70	3,90	4,10	4,30
BRD		2,680	2,686	2,691	2,697
MTD(IAV)		2,761	2,751	2,741	2,731
MTD(TAV)		2,786	2,776	2,765	2,755
Film thickness (micron)		6,699	7,071	7,443	7,815
VFB (%)		77,03	81,41	85,80	90,21

©



DENSITY3 © - Predicted Asphalt Mix Properties for given Grading and Specified Binder Type and R&B temp (only for Type 7)

DATE: 16/05/2017
SAMPLE: Bituminous Treated Base (BTB)
DESCRIPTION: Continuously graded asphalt (26.5mm maximum size)
Binder type:

OB	bit-rubber	Latex bit	EVA bit	SBS bit	B-R + extender	R&Btemp
1	2	3	4	5	6	7

BinderNo	R&Btemp
7	46

Fraction of intraparticle voids filled with binder 0,25

GRADING Metric units	
SIEVE(mm)	% passing
75	100,00
63	100,00
50	100,00
37,5	100,00
28	100,00
20	86,10
14	79,95
10	63,03
7,1	53,86
5	46,14
2	33,66
1	24,68
0,6	18,18
0,3	10,31
0,15	9,74
0,075	5,12

ATTERBERG LIMITS
(Casagrande Apparatus)

PI	LL	PL	LS
0,00	0,00	0,00	0,00

Density and shape information

ARD(CF)	ARD(FF)
2,991	2,928

BRD(CF)	BRD(FF)
2,958	2,893

Want to change model - yes or no? Yes = 1
No = 2
Answer here 1

ASPHALT OUTPUT PREDICTIONS

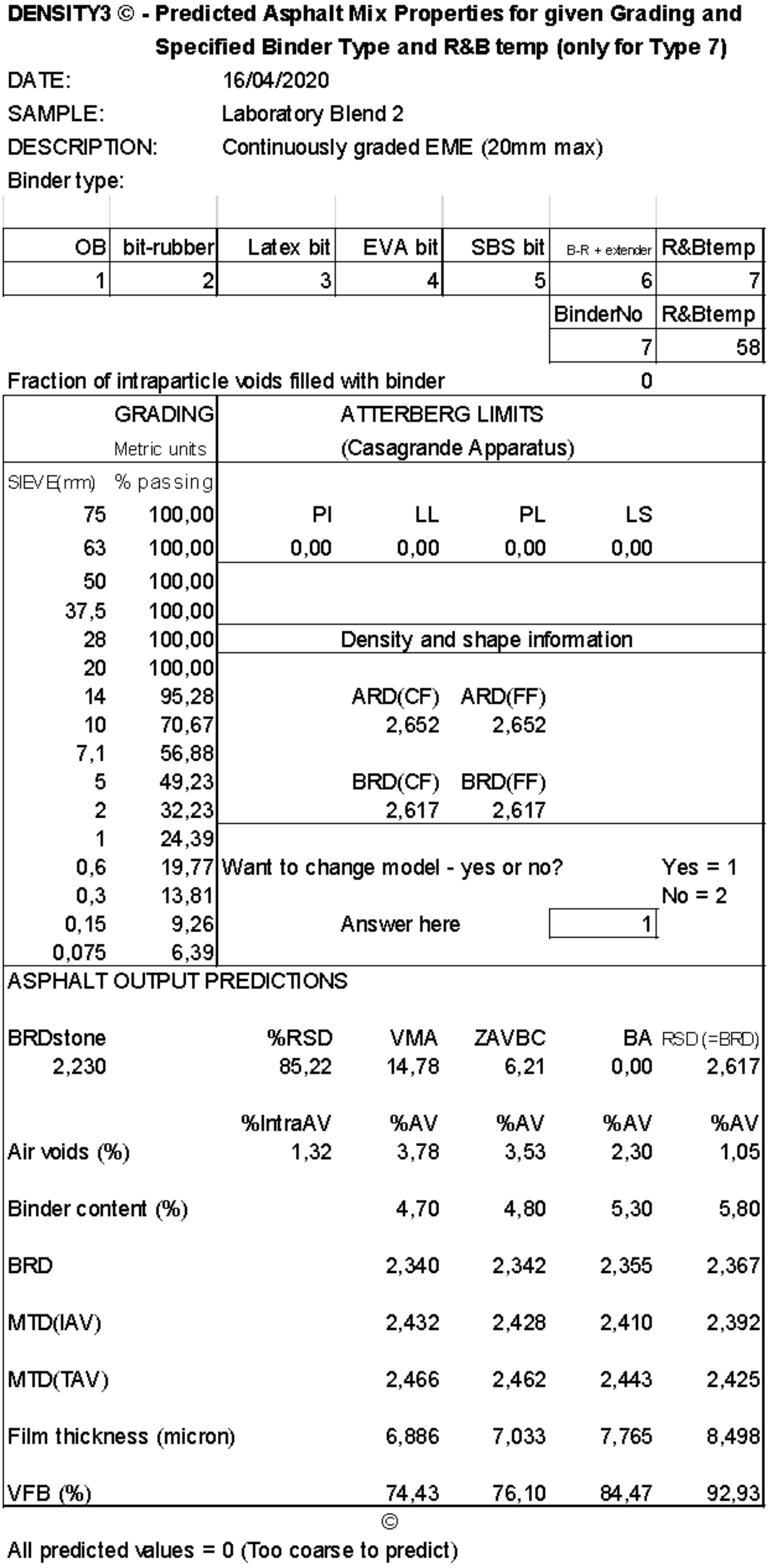
BRDstone	%RSD	VMA	ZAVBC	BA	RSD (=BRD)
2,604	88,05	11,95	4,49	0,10	2,958

	%IntraAV	%AV	%AV	%AV	%AV
Air voids (%)	0,87	2,04	1,48	0,91	0,35
Binder content (%)		3,70	3,90	4,10	4,30
BRD		2,705	2,710	2,716	2,721
MTD(IAV)		2,761	2,751	2,741	2,731
MTD(TAV)		2,786	2,775	2,765	2,755
Film thickness (micron)		6,699	7,071	7,443	7,815
VFB (%)		82,91	87,62	92,35	97,10

©

The predicted results for R&B value the binder of 48 and 46 instead of the design value of 52 clearly show that the mix closes up when the binder becomes softer. This is not something that contractors can control during construction and engineers are strongly advised to take note of this.

Table 7- Predicted Results for High Modulus Asphalt (EME)



DENSITY3 © - Predicted Asphalt Mix Properties for given Grading and Specified Binder Type and R&B temp (only for Type 7)

DATE: 16/04/2020
SAMPLE: Laboratory Blend 2
DESCRIPTION: Continuously graded EME (20mm max)
Binder type:

OB	bit-rubber	Latex bit	EVA bit	SBS bit	B-R + extender	R&Btemp
1	2	3	4	5	6	7

BinderNo	R&Btemp
7	58

Fraction of intraparticle voids filled with binder 0

GRADING Metric units	
SIEVE(mm)	% passing
75	100,00
63	100,00
50	100,00
37,5	100,00
28	100,00
20	100,00
14	95,28
10	70,67
7,1	56,88
5	49,23
2	32,23
1	24,39
0,6	19,77
0,3	13,81
0,15	9,26
0,075	6,39

ATTERBERG LIMITS
(Casagrande Apparatus)

PI	LL	PL	LS
0,00	0,00	0,00	0,00

Density and shape information

ARD(CF)	ARD(FF)
2,652	2,652

BRD(CF)	BRD(FF)
2,617	2,617

Want to change model - yes or no? Yes = 1
No = 2
Answer here 1

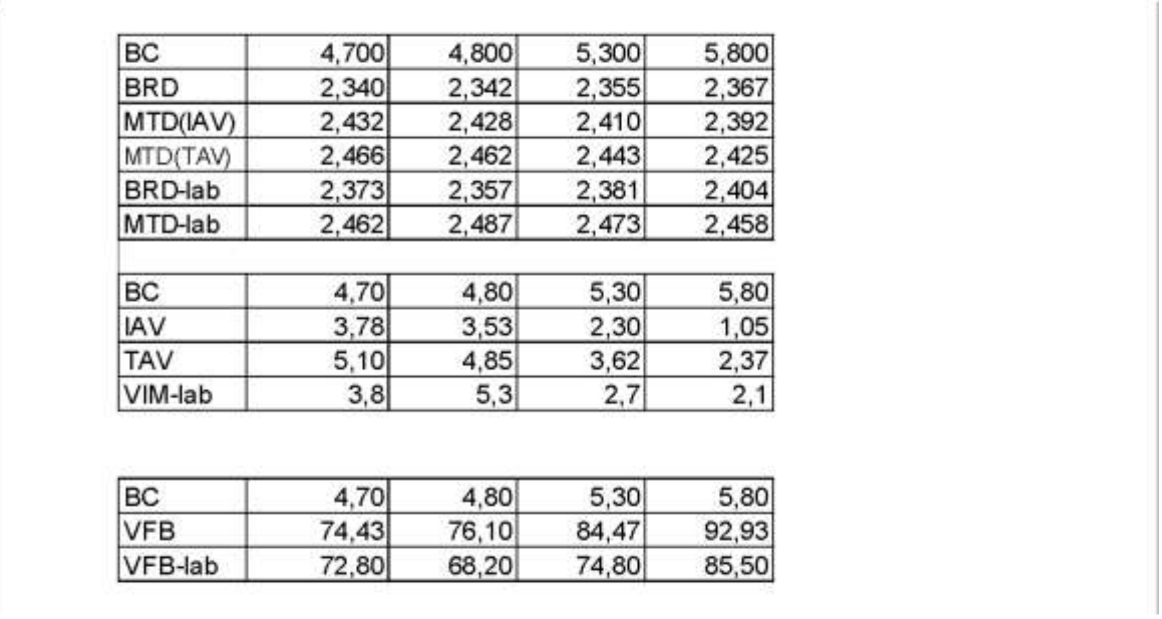
ASPHALT OUTPUT PREDICTIONS

BRDstone	%RSD	VMA	ZAVBC	BA	RSD (=BRD)
2,230	85,22	14,78	6,21	0,00	2,617
	%IntraAV	%AV	%AV	%AV	%AV
Air voids (%)	1,32	3,78	3,53	2,30	1,05
Binder content (%)		4,70	4,80	5,30	5,80
BRD		2,340	2,342	2,355	2,367
MTD(IAV)		2,432	2,428	2,410	2,392
MTD(TAV)		2,466	2,462	2,443	2,425
Film thickness (micron)		6,886	7,033	7,765	8,498
VFB (%)		74,43	76,10	84,47	92,93

©

All predicted values = 0 (Too coarse to predict)

Table 8 - Predicted and Laboratory Results of High Modulus Asphalt (EME)



BC	4,700	4,800	5,300	5,800
BRD	2,340	2,342	2,355	2,367
MTD(IAV)	2,432	2,428	2,410	2,392
MTD(TAV)	2,466	2,462	2,443	2,425
BRD-lab	2,373	2,357	2,381	2,404
MTD-lab	2,462	2,487	2,473	2,458

BC	4,70	4,80	5,30	5,80
IAV	3,78	3,53	2,30	1,05
TAV	5,10	4,85	3,62	2,37
VIM-lab	3,8	5,3	2,7	2,1

BC	4,70	4,80	5,30	5,80
VFB	74,43	76,10	84,47	92,93
VFB-lab	72,80	68,20	74,80	85,50