Laboratory experience with the application of monotonic triaxial test on the cold recycled asphalt mixes

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ABSTRACT

Besides cracking, cold recycled asphalt mixtures are deteriorated due to permanent deformation as well. For evaluating these rutting properties in order to allow a suitable pavement design based on the significant mechanical properties of cold recycled asphalt materials, monotonic triaxial tests can be applied. Specimens with a diameter of 150 mm and a height of 300 mm are subjected to monotonically increased vertical compression stress until specimen failure whereas a radial confining stress is maintained constant. By conducting triaxial tests with varied confining stress, the shear strength for various stress conditions will be evaluated. This paper is focused on the description of the test device, the test methodology as well as the assessment of test results. Further the specimen preparation procedures are discussed as identified as significantly relevant for simulating the field performance of cold recycled asphalt mixtures. Finally the effect of variation in binder content (bituminous binder – emulsion and foamed bitumen) and hydraulic binder are discussed.

Keywords: Cohesion, Emulsions, Foam, Reclaimed asphalt pavement (RAP) Recycling

1. INTRODUCTION

The quality of cold recycled mixes or Bitumen Stabilized Materials (BSM) is very often assessed by means of the indirect tensile strength (ITS) or CBR test. Both tests are empirical and deliver a mathematically determined index or empirical value, not a relevant engineering material characteristic. Therefore, the utilisation of the tests, which are quick and easy on one hand, is solely empirical and yielding just one value under specific defined conditions (with no other information or wider context) on the other hand. This has been criticised by many experts. Specialists in road construction have repetitively tried to introduce more appropriate testing, the output of which could be used for pavement structure design in combination with mechanistic-empirical design methods, linear-elastic multi-layer pavement design software and finite element method software.

Despite of some disadvantages, the monotonic triaxial test that determines the shear parameters of granular mixtures is probably one of the suitable tests to classify this type of material, particularly if the mixture is characterised by a low proportion of bituminous or hydraulic binder. Besides the advantages mentioned in the abstract, concerning the possibilities of simulating the impact of the surrounding material which resists the deformation exerted within the pavement structure, we should also mention the possibility of exploiting the triaxial device for other types of tests as well, these being the cyclic triaxial test that determines the resilient modulus M_r (in case of short-term tests) or permanent deformation ε_p (in case of long-term tests). The output from both types of triaxial tests which, however, go beyond the scope of this paper, constitute another reason for pacing triaxial testing at the centre stage of any mechanistic approach to pavement design, [1]. The main disadvantage of using the monotonic triaxial test for cold recycled mixes is its requirements on time and, primarily, the difficult handling of heavy test specimens in combination with a still very heavy test mould (each specimen weighs 12.5 kg; with the mould and membrane, the weight is approximately 45 kg). Moreover, the test poses high demands on the operator's skills and experience during test performance. Another disadvantage is associated with the introduction of any new test – the majority of laboratories in Europe do not have the equipment; along with financial aspects, this also brings a certain unwillingness towards novel approaches or changes in the testing field. Therefore, it is first necessary to verify the benefits of the test in comparison to other more simple tests, or search for solutions to simplify this test and increase its reproducibility.

The idea of creating a modified triaxial device for BSM testing has come from JENKINS and his team (South Africa). He has researched this topic successfully for several years and, therefore, the test methods described below, and some other experience with the application of monotonic triaxial test were adopted to provide comparability of the values obtained.

2. THE ESSENCE OF THE MONOTONOUS TRIAXIAL TEST

During triaxial test, a cylindrical test specimen is stressed in three mutually perpendicular directions. The major principal stress σ_1, acting in the direction of the specimen's axis, i.e. perpendicular to the bases, simulates the vertical stress caused by the crossing of a vehicle. The minor principal stress σ_3, or the confining stress, is perpendicular to the shell of the specimen, is of constant value at all locations and simulates the resistance of the surrounding materials within pavement structures to the deformation caused. During a monotonous triaxial test, the specimen is stressed (until failure) by vertical stress σ_1 generated by a constant increase of deformation in time. During the test, the confining stress σ_3 is set to a constant value for each individual experiment where the value is maintained for the entire duration of test specimen loading by means of air pressure in a rubber membrane (see Chapter 5). The $\sigma_1 - \sigma_3$ difference is called the deviatoric stress q; it is the radius of Mohr circle at the same time (Fig. 1). These are used to determine the critical combination of normal and shear stresses at the moment of failure of the test specimen. When at least three Mohr circles are plotted (of which each relates to a different value of confining stress), a tangent to such circles can be construed – the so-called Mohr-Coulomb failure criterion. Any combination of principal and shear stresses above the line results in a failure of the test specimen, thus the compacted layer of the material assessed.

The equation of Mohr-Coulomb failure line can be expressed mathematically by the following formula:

$$\tau = c + \sigma \tan \varphi$$

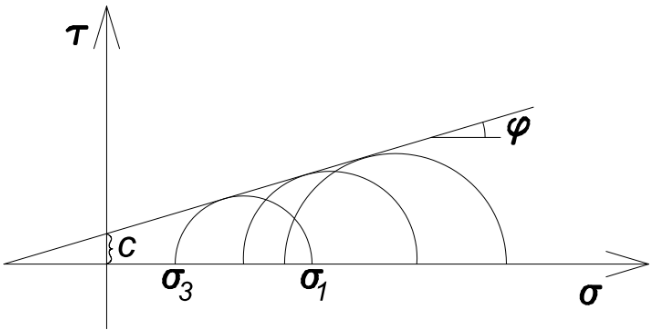

Figure 1: The Mohr-Coulomb failure criterion principle

In other words, the mathematical formula known as the Mohr-Coulomb equation is used to calculate the shear strength of materials based on the principal stress σ, internal friction angle φ and cohesion c. The φ and c shear parameters can be obtained from the Mohr circles where φ is the angle between the failure criterion line and the horizontal axis and c is the distance from the intersection of this line with the vertical axis from the beginning of the coordinate system.

Shear strength is an important property of BSM, taking in consideration the material's behaviour in a pavement layer. In behaviour, BSM is quite similar to uncompacted layers of granular materials (UGM) which results in an almost negligible capacity to transfer tensile stress. Shear strength must be used to develop the capacity to distribute loading onto a larger area which is the essential task of base and subbase layers. Simply said, if the meaning of individual parameters should be defined, cohesion c can be viewed as a certain "adhesiveness" of the material while φ is basically the level of resistance to friction depending primarily on the granular material properties. Shear strength is then the overall resistance to shifting at the contact points of grains created by particle "interlocking", physical and chemical bonds [1].

The size of shear strength is affected primarily by material granularity (including maximum particle size), fine particle content and properties and geometric properties of the particles. Another significant parameter is the bulk density, according to LONG and VENTURA [5] a higher bulk density usually results in a higher cohesion and internal friction angle. Besides, shear strength is also affected by confining pressure value as is clearly visible in the stress-strain diagrams depicting the course of stress and deformation during the monotonic triaxial test for various confining stress levels (see Fig. 2). The higher the confining stress on the test specimen, the higher the force that specimen can transfer. The last important aspect is the moisture content of the mix. According to LONG and VENTURA [5], a higher moisture content results in lower cohesion. In contrast to the deviatoric stress which is independent of pore pressure because water does not carry shear forces, shear strength decreases due to pore pressure.

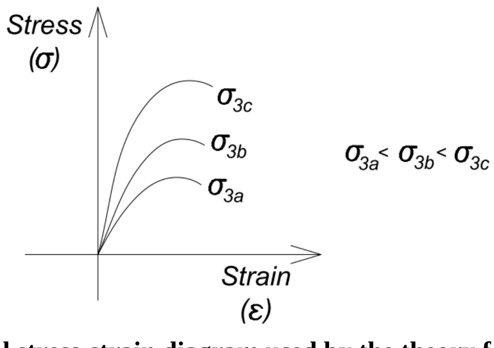

Figure 2: Typical stress-strain diagram used by the theory for triaxial testing

3. MIX DESIGN

Table 1 summarizes mix design of 5 investigated cold recycled mixes. The designs were selected in a way to show representation of different types of used materials or binders. All designed mixes contained the same type of screened reclaimed asphalt material (RAP) with 0/22 mm grading originating from the same source (hot mix asphalt plant Středokluky). Nevertheless the homogeneity of RAP was quite poor, which is typical for the Czech circumstances or more generally it is typical for these materials if selective cold milling for each construction site is not done. This fact influenced greatly the test results and complicated setting of any strong final conclusions with appropriate repeatability of determined data. The determined bitumen content of 5.6 % for RAP 0/22 should be considered as just approximate, because the composition of RAP differed even within a single batch not to mention the difference between various batches. Because of that it was very important to perform all measurements at once. Testing of some related values using specimens made later from another batch is not recommendable because the RAP composition influences the final mix characteristics.

Table 1: Mix designs examined

	Mix D	Mix K	Mix L	Mix C	Mix BC
RAP 0/22	93,0%	95,0%	94,0%	94,5%	47,0%
Recycled concrete	-	-	-	-	47,0%
Foamed bitumen	**4,5%**	**2,5%**	**2,5%**	-	-
Bituminous emulsion	-	-	-	**3,5%**	**3,5%**
Cement	-	-	**1,0%**	-	-

To compare the effect of different type of recycled material, recycled concrete was selected besides the RAP. This material which is contained in mix BC was partly re-crushed in the laboratory of the Department of Road structures at CTU in Prague for getting 0/22 mm grading. The original material came from the ongoing modernization of the key Czech motorway D1. In one mix cement was applied as active filler. The used cement was classified CEM II / B 32.5 according to EN 197-1. Mix C and mix BC contained cationic slow-breaking bituminous emulsion C60B8 according to EN 13808 which is commonly used in the Czech Republic. Mix D, mix K and mix L were based on the foamed bitumen technique. For the production of foamed bitumen commonly used straight-run bitumen 70/100 was applied according to EN 12591. When preparing the foamed bitumen, there was 3,8 % of water added to the bitumen, whereas the amount was determined in accordance with the procedure which is recommended for cold recycling technology by Wirtgen Manual [7]. Foamed bitumen was injected into the cold recycled mix under the temperature between 160 °C and 170 °C by means of the Wirtgen WLB10S laboratory equipment. All cold recycled mixes were mixed using a twin-shaft compulsory mixing unit Wirtgen WLM 30. The optimal moisture content of the cold recycled mix was determined according to ČSN EN 13286-2.

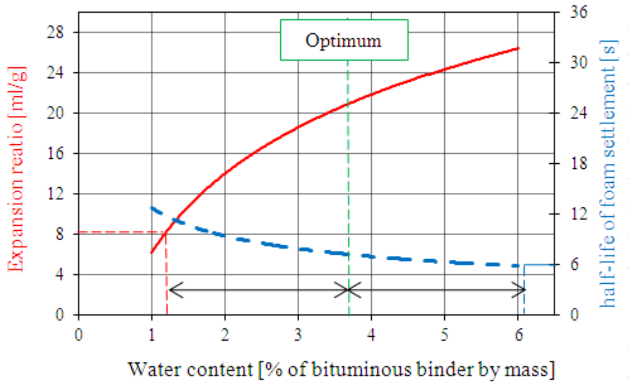

Figure 3: Determining the optimum water content used for foamed bitumen production

Setting of the optimal water content added to the foamed bitumen is shown in Fig. 3. Foamed bitumen is characterized by the expansion ratio ER (ml/g) and the half-life of foam settlement τ½ (seconds). Both parameters are strongly dependent on the kind and origin of the bituminous binder, the amount of the pressurized air added and the pressure of the water injected into the hot bitumen. The intensity and efficiency of the foaming effect can be influenced by basic physical conditions such as temperature, moisture and pressure. Finally the optimal amount of the foaming water was set at 3,8 % of bitumen in order to achieve optimal combination of high expansion ratio and still sufficiently long half-life.

4. MANUFACTURING AND TREATMENT OF LABORATORY SPECIMENS

As has been mentioned already, the use of a classic triaxial device utilised in geotechnics is not appropriate for cold recycled mixes. The most frequent application of such mixes is in pavement base and subbase layers which corresponds with the maximum grain size which, in such mixes, can be up to 45 mm. Due to that, the test device had to be modified in the past to allow testing cylindrical specimens with 150 mm diameter and 300 mm height (to maintain a suitable slenderness ratio) which are dimensions verified by JENKINS in the past. Laboratory specimens were prepared by putting the cold recycled mix in cylindrical moulds and compacted by manual press when applying static pressure of 5,0 MPa. The compaction procedure used in countries like CZ is described in more detail e.g. in [8]. The test specimens were compacted in a single layer, on the contrary to the methodology presented in [1] that requires the test specimens to be compacted layer by layer by the dynamic method using a Kango Hammer. One-take compaction of test specimens was selected due to negative experience with layer-by-layer compaction of test specimens made of treated soil mixtures. Specimens compacted layer-by-layer tended to fail at the layer seams which affected the maximum stress the specimen could transfer and, therefore, the shear stress results obtained.

Subsequently, the test specimens were subjected to an accelerated curing process which is a procedure recommended within the CoRePaSol international project for cold recycled mixes with 1 % cement and less, [9]. According to this procedure specimens were stored for the first 24 hours at 90-100% relative humidity and a temperature of (20±2) °C, in order to simulate the initial moisture content of the mixture after paving and compaction of the fresh mix. This was done by keeping the specimens in the mould or by putting them into a suitable plastic bag. After that the specimens were removed from the bag and cured unsealed for additional 72 hours at 50 °C. The measurements taken within the CoRePaSol project suggested that test specimen properties after accelerated curing roughly correspond with the properties after 21 days of curing under laboratory conditions. The specimens were left under laboratory conditions for another 7 days; this resulted, in just 11 days, in achieving the properties corresponding approximately to the properties after 28 days in laboratory conditions.

The basic volumetric parameters were determined for the test specimens prepared, see Table 2. Before the triaxial test was conducted, the test specimens were kept for at least 12 h at 25 °C for temperature conditioning.

5. PRINCIPLES OF THE TRIAXIAL TESTING PERFORMED

The test method was adopted from JENKINS; it is described in detail e.g. in [2]. Fig. 4 depicts how the test specimen is stressed from the top by major principal stress while the specimen is placed in a special mould which was designed, adjusted and manufactured according to the original experience of JENKINS by the Wirtgen during the CoRePaSol project. The hose brings pressurised air that generates the confining stress into the rubber membrane (see Fig. 5 for details) located around the test specimen in the mould. During preliminary testing, we tried using a thin natural rubber membrane as recommended in literature and produced by a special method e.g. at the Stellenbosch University. However, it has a major disadvantage of poor durability and sensitivity to handling when the thin rubber layer wore out very quickly. A new type of used massive rubber membrane is heavier but also characterised by a significantly improved resistance, which also simplifies handling. It was not necessary to open the mould between individual tests, it sufficed to disconnect the membrane from air supply, take the bottom base off, lift the mould with the membrane and simply slide out the broken test specimen. A new test specimen was placed on the base and the mould, together with the membrane, was slid onto the new specimen. This simplification which reduced significantly the time requirements was enabled by using a membrane that can withstand such handling.

Due to a minor problem associated with the manometer used, the confining stress levels were set to rather unusual values of 0, 90, 135 and 210 kPa; however, this does not affect the determination of shear parameters at all. The test specimens were stressed by a constant speed of 2,1 – 2,6% strain per minute; for test specimens of 300 mm height, this corresponds with the speed of 6,3 – 7,8 mm per minute. Again, this value was taken from JENKINS [1] to provide comparability of the values measured. Other experts working on the triaxial test for cold recycling mixes also adopt this speed, e.g. GONZALEZ [6], whose work has been an important source of data for this paper as well.

Figure 4: Stressing the test specimens during the tests

Figure 5: Detail of the special mould with rubber membrane inside

Figure 6 displays the failed laboratory specimens after the triaxial test. Contrastingly to treated soil materials which are characterised by a shear area along which a part of the specimen is sheared, the cold recycled mixes present a distinctively different deformed shape. After the test, the specimen is almost barrel-shaped with a slight enlargement, usually in the central part. This kind of deformation is most probably generated due to the presence of bituminous binder showing the elastic behaviour of the material and the effect of individual particles being bound by the binder. Tested specimens have a similar shape also in the case of compression strength testing.

Figure 6: Typical examples of failed test specimens

6. DISCUSSION OF RESULTS

The experiments were conducted with mixes of various bituminous binder contents (foamed bitumen or bituminous emulsion), in one case, even a mix with 1 % cement was tested. Mixes with higher cement content were not investigated as, according to JENKINS [4], stress-dependent behaviour only applies to mixes without major quantities of active filler. This statement is supported by his findings from experimental measurements where the addition of larger quantities of cement resulted in the internal friction angle decreasing down to 0°.
The values of shear parameters φ and c determined by the monotonic triaxial test were compared to one another and, subsequently to the findings from other researchers. For the sake of complexity, the parameters observed were also compared to selected mixes of similar composition as found in literature. However, the comparison is merely approximate although the mixes have similar binder contents; the mixes might differ in granular composition, binder type, compaction method or test specimen curing times.

The following diagrams depict the Mohr circles for all mixes researched; specific shear parameter values (including the correlation coefficient) are indicated in Table 2 as well.

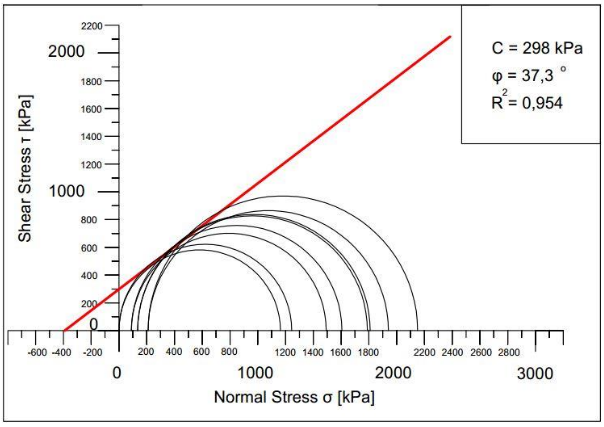

Fig. 7: Results of triaxial test - mix D (4,5 % foamed bitumen)

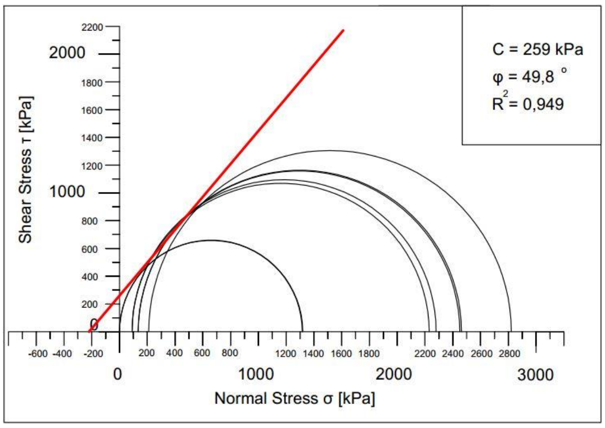

Fig. 8: Results of triaxial test - mix K (2,5 % foamed bitumen)

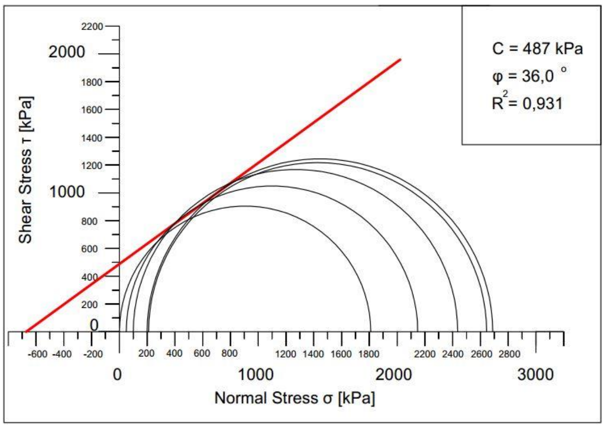

Fig.9: Results of triaxial test - mix L (2,5 % foamed bitumen + 1 % cement)

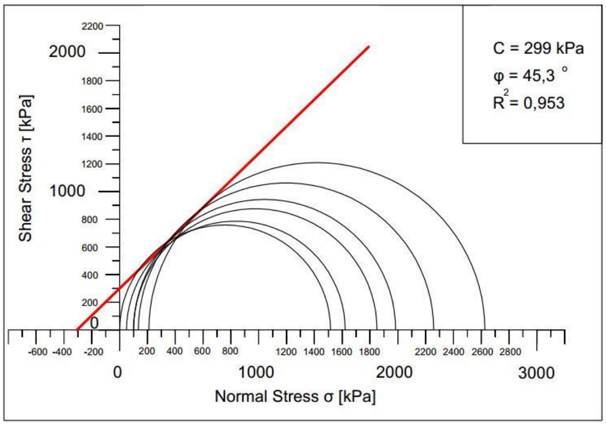

Fig. 10: Results of triaxial test - mix C (3,5% bituminous emulsion)

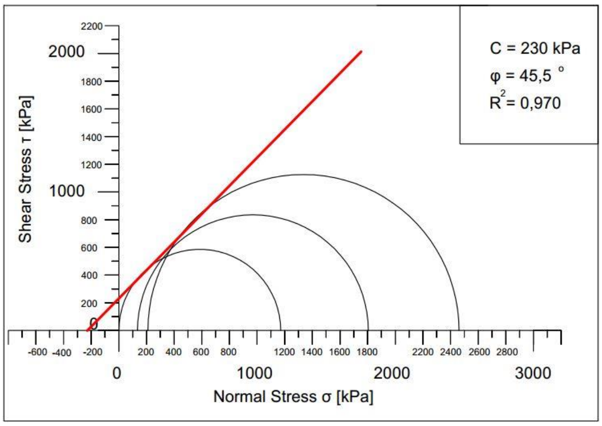

Fig. 11: Results of triaxial test - mix BC (3,5% bituminous emulsion, RAP + recycled concrete)

According to GONZALEZ [6], the impact of the foamed bitumen content results in a smaller internal friction angle φ. However, according to his findings, a higher proportion of foamed bitumen has no significant effect on the cohesion value c. Similarly, JENKINS [4] states that a higher proportion of foamed bitumen decreases the φ. But contrastingly to GONZALEZ he claims that it also increases cohesion c. A comparison of the shear parameters determined for mix D (4,5 % foam) and mix K (2,5 % foam) confirmed these findings; the reduction of the internal friction angle is really noticeable while the increase of the cohesion value is not significant; therefore, we can agree with both authors. Moreover, the finding confirms the comparison of values stipulated for mix L (2,5 % foam and 1 % cement) to the values of the mix tested by JENKINS [3]. For a mix with 2,3 % foam and 1 % cement, he determined c = 414 kPa and φ = 44,2°. Compared to mix L, this mix had less foamed bitumen; therefore, it had lower cohesion and a bigger internal friction angle.

Table 2: Determined characteristics of the investigated cold recycled mixtures

Cold recycled mix	φ	C	R^2	Bulk density	ITS	Stiffness modulus
	[°]	[kPa]	[%]	[g/cm^3]	[MPa]	[MPa]
D	37,34	298	95,4%	2,091	0,36	1036
K	49,87	259	95,0%	2,128	0,41	1596
L	36,02	487	93,1%	2,217	0,52	2957
C	45,48	230	97,0%	2,070	0,35	1164
BC	44,25	299	95,3%	2,067	0,41	1784

Another aspect under observation was the impact of cement additions on shear parameters of cold recycled mixes. According to LONG and VENTURA [5], higher cement content result in higher cohesion and smaller internal friction angle; this corresponds with the shear parameters of mixes K (2,5 % foam) and L (2,5 % foam and 1 % cement). Contrastingly to the impact of foamed bitumen, the effect of cement additions on the cohesion value is significant. This is also confirmed by a comparison of mix D to the mix tested by GONZALEZ [6]. For a mix with 4 % foam and 1 % cement, he obtained shear parameters of c = 343 kPa and φ = 27°. Compared to mix D, this mix has slightly lower foamed bitumen content but, primarily, a higher cement content which outweighs the impact of the foam. A similar situation occurs in the case of comparing mix K to the mix tested by JENKINS [3] which has already been mentioned above. Again, the mix with 2,3 % foam and 1 % cement, with shear parameters of c = 414 kPa and φ = 44,2° demonstrates a higher c and a lower φ than mix K, which has a zero cement content. The addition of 1 % cement outweighs the effect of a minor reduction in the foam content again (by 0,5 % in this case).

Mixes C and BC with bituminous emulsion contents differed solely as to the granular component compositions, namely, in mix BC, one half of RAP was replaced by recycled concrete. Due to that, these mixes scored similarly in shear parameters. The values measured for mix C and for a mix of a similar composition tested by JENKINS [1] differ in the cohesion value. For this mix with 3.3 % bituminous emulsion, he determined c = 95 kPa and φ = 41,4; that means that the internal friction angle is similar while there is a rather noticeable difference between the cohesion values. This might be caused by the aforementioned differences which could appear in the mix granularity, different types of bituminous emulsion, test specimen preparation methods or different conditions and time of specimen curing.

Fig. 12 shows the Mohr-Coulomb failure criterion for individual mixes when entered in a single diagram. With respect to the fact that shear strength depends on two parameters, φ and c, it is not quite clear how the mixes should be sorted from best to worst. The “order” of mixes differs significantly for different values of normal stress. The diagram is very illustrative as to the impact of a higher content of foamed bitumen in mix D and a higher cement content in mix L, both of which results in a smaller internal friction angle and, therefore, in poor results in the higher normal stress range. However, in the lower principal stress range, mix L outperforms all other mixes thanks to its high cohesion values (also a consequence of the cement addition). The diagram also shows the similar behaviour of mixes C and BC where mix BC, with a partial replacement of RAP by reclaimed concrete, scores slightly better when compared to mix C which only contains RAP. For normal stress of up to 500 kPa, mix L seems to be the best while mix K has the best scores for normal stress exceeding 500 kPa. With respect to the fact that the usual normal stress to which materials in the base and subbase layers are exposed is significantly lower than 500 kPa, mix L can be considered the best mix from the perspective of a critical combination of principal and shear stress.

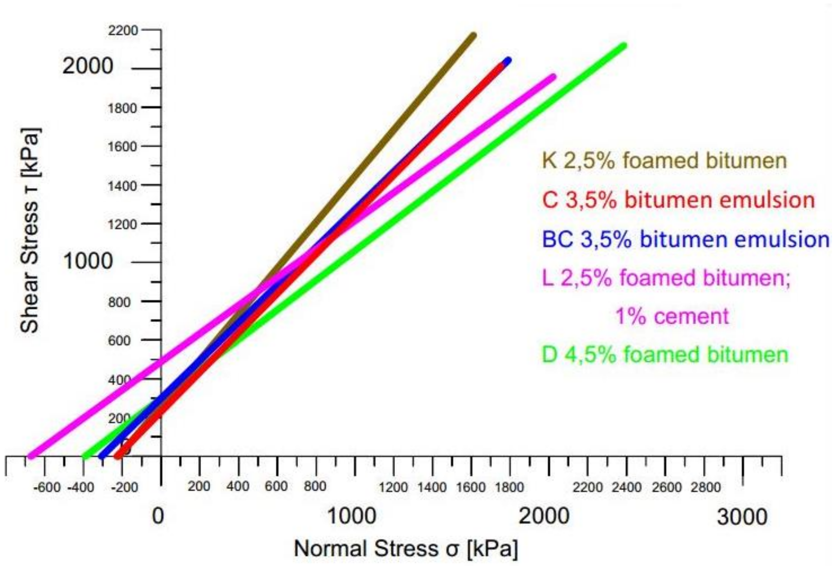

Figure 12: Mohr-Coulomb failure criterion for all tested cold recycled mixtures

Table 2 indicates, besides the results of the triaxial test conducted, also the indirect tensile strength and stiffness modulus determined by repeated indirect tensile stress test on cylindrical specimens (IT-CY method) measured under 15 °C after 14 days of specimen curing. For a certain suggestion of the direction to be followed by research activities in the future, an envisaged description of the possible dependencies can be mentioned as an example – these are the relationship between the shear parameters and strength characteristics determined by the commonly used BSM tests. The simple linear regression between indirect tensile strength and cohesion for example (Fig. 13), presents a possibility of a linear relationship between these variables; however, the extent of the triaxial testing performed so far is still too small to allow any relevant, statistically supported conclusions.

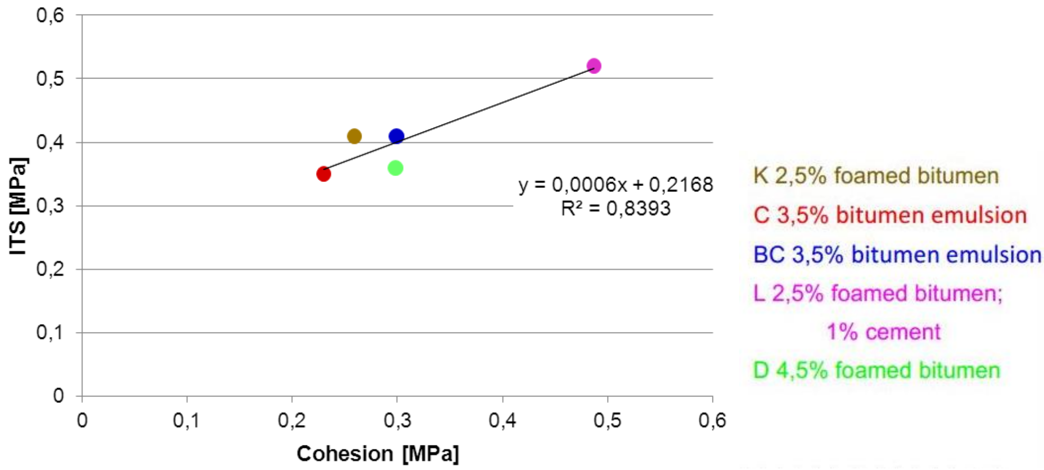

Figure 13: Linear regression for ITS and cohesion

7. CONCLUSIONS

This paper summarises the so far gained experience of shear parameters measured for cold recycled mixes by means of a modified triaxial device in Central Europe. Several series of initial tests conducted with test specimens of 300 mm height and 150 mm diameter confirmed that the time requirements of the tests are higher than those of simple empirical tests like ITS; however, the difference is not as huge and should not serve as the overruling criterion in the decision-making on alternative test method applicability. The most important problem is the weight of the test specimens and the special mould in which the specimens are placed for the test. The mould is not a part of the press apparatus that is used to load the specimens; therefore, the mould (with the specimen inside) must be taken out of the press when the failed specimen is being replaced by a new one; this means handling approximately 45 kg at the moment. With respect to the maximum particle size (up to 45 mm in cold recycled mixes), the specimen dimensions (and, therefore, weight) cannot be reduced; drilling smaller test specimens out of the existing test specimens of the aforementioned dimensions is questionable as well – it has been repeatedly proven, particularly in a number of other tests performed for cold recycled mixes, that the drilling or cutting of test specimens usually breaks them. On the other hand, one of the easier solutions to choose in the future is reducing the weight of the test mould. Currently various material alternatives are analyzed for such moulds to reduce the weight of the mould (triaxial cell) which is an auspicious approach. Also the method of connecting the individual parts of the triaxial cell together should be simplified.

Another partial improvement done by Wirtgen within the CoRePaSol project – the use of a more resistant rubber membrane – has been tested within the experiments conducted and is described in this paper. The resistant membrane is heavier in comparison to the original, thin natural rubber membrane. However, the benefits of the rubber membrane in relation to improved resistance to wearing out outweigh such disadvantage.

In general, experience with modified monotonic triaxial test could be summarised to say that the obstacles preventing its implementation are not impossible to overcome, particularly if the weight of the test mould (cell) can be efficiently reduced. Otherwise, this performance-based test has a great potential for cold recycled mixes, primarily for those with low contents of the binders applied, the behaviour of which is more similar to unbound materials (UGM) where cohesion and shear parameters generally play a major role and the triaxial test can in a better way describe the behaviour of such material.

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