4C-Packing - User's manual

Version 3.0

Claus Pade, Concrete Centre
Lars Nyholm Thrane, Concrete Centre
Martin Kaasgaard, Concrete Centre

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Concrete

Contents

1. Introduction

4C-Packing has been developed as a tool for use in concrete proportioning. 4C-Packing calculates the packing of aggregate, but it can also be used to calculate the packing of any particle system on the assumption that only gravitational force exist between the particles. Also finding the best fit combination of aggregates to a target grading curve can be performed.

In the proportioning of concrete, the programme can be used to compose the aggregate skeleton in order to make it as dense as possible. A dense aggregate skeleton means that the concrete can be mixed with a minimum of paste, and thus a minimum of cement. Reduced paste content has a beneficial effect on a number of concrete properties, including a reduction in shrinkage and heat generation during hardening. In addition the concrete becomes more economic and environment-friendly.

This User's Manual describes how to use the different functions of the 4C-Packing software.

Appendix A is a guide to the installation of 4C-Packing.

Appendix B is a guide to experimental determination of eigen-packing.

Appendix C is a guide to experimental determination of the loosening-effect parameter called the "Mu-value".

1.1 Input and output for 4C-Packing

The programme's calculations are based on a mathematical model originally developed for ideal spherical particles. In order to use the model for non-spherical particles, material properties such as particle density, particle size distribution and eigen-packing are necessary input parameters in the model on which the computer-programme is based. The input and output of the 4C-Packing are provided in Table 1.

	Input	Output
Material	Particle density Size distribution Eigen-packing Unit cost	
Calculations	"mu"value GC subdivision	Packing density (calculated packing) Packing diagrams Combined grading curve Concrete mix Grading factor

Table 1: Input and output for 4C-Packing.

If the "Concrete mix" option is used it is also necessary to provide input values of "excess paste" in L/m^3 of concrete (default is 0), "w/c ratio" (default is 0.5), "Air volume" in L/m^3 (default is 0), "Cement density" in kg/m^3 (default is 3150) and "Cement cost" in Euro/ton (default is 80). The output is then a mix design in kg/m^3, the density of the mix design in kg/m^3 and the cost of the mix design in Euro/m^3. Other currencies can be selected.

Eigen-packing
The eigen-packing is an input parameter for 4C-Packing calculations. The packing of a material (also called eigen-packing) is a number in the range 0 to 1, which indicates how densely the material is packed in a unit volume, i.e. how large a part of the total volume is constituted by solid material, see Figure 1.
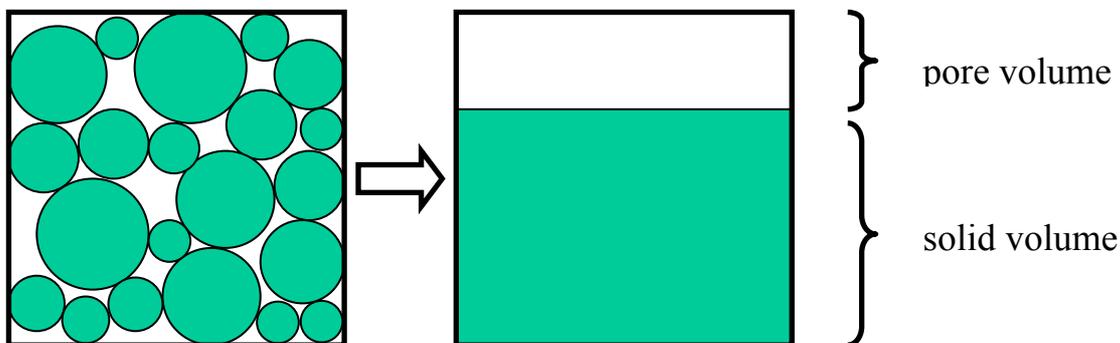

Figure 1: Definition of eigen-packing: eigen-packing = solid volume / total volume.

The eigen-packing can be determined experimentally by packing of the material in a container. The value of the eigen-packing will depend on the method of determination. The method used by DTI is described in Appendix B. Different methods of eigen-packing determination will provide different results when calculating the packing of a combination of aggregates. Thus, only results based on the same method of eigen-packing determination should be compared.

Using the DTI method of eigen-packing determination typical values for Danish aggregate with rounded particle shape are in the range 0.60 - 0.70, whereas crushed coarse aggregate typically has values in the range 0.50 - 0.60.

Particle density and size distribution
Particle density and size distribution of each material are inputs to 4C-Packing and are determined experimentally. There are standard methods for determining these properties, and the procedure will therefore not be discussed further here.

"Mu-value"
 The "Mu-value" is an interaction factor used in the packing calculations. It indicates maximum ratio (size) between small and large particles possible without the smaller particles inter-

fering with the packing of the larger particles, i.e. if the size ratio is larger than the "Mu-value" the smaller particles are pushing the larger particles apart reducing packing density.

The "Mu-value" can be determined experimentally, see Appendix C.

GC subdivision
In the calculations, each of the defined sieve jumps is subdivided into a number of smaller jumps, specified as the space *GC-subdivision* (distribution curve subdivision) in the upper right corner of the screen picture. Increasing the number of subdivisions improves the accuracy of the packing calculation, but increases the calculation time. Normally a *GC-subdivision* of 3 will be sufficient; it means that each sieve jump in the distribution curve is subdivided into 3 equal size intervals, on which the calculation is then based.

Results
The result of the calculations in 4C- Packing is a graphical presentation of the possible combinations of two or three selected materials. On this basis, a combination of aggregate with e.g. high packing, low sensitive to variations and good economy can be chosen.

In addition, the combined particle size distribution curve for any combination of materials can be calculated and presented graphically in binary and ternary diagrams.

4C-Packing can also calculate the combination of selected materials that most closely fits a preferred grading curve (target grading curve).

The parameter "Grading factor" is also calculated as the sum (cumulation) of the passing-% on the sieve sizes 0.125, 0.25, 0.50, 1, 2, 4, 8, 16, 31.5 and 63 mm, i.e. if all material is passing 0.125 mm the "Grading factor" is 1000.

Based on the combination of aggregates found using the grading curve fitting or packing calculations the "Concrete mix" option can be used the calculate the proportions and costs of a concrete mix design.

2.   Start-up of 4C-Packing

When 4C-Packing icon on the desktop is activated the window shown in Figure 2 will appear. The two menus ("Settings" and "Help") in the upper left corner of the starting screen picture make it possible to carry out adjustments of the programme regarding language, sieve sizes, user name, etc.

Figure 2: Start window in 4C-Packing.
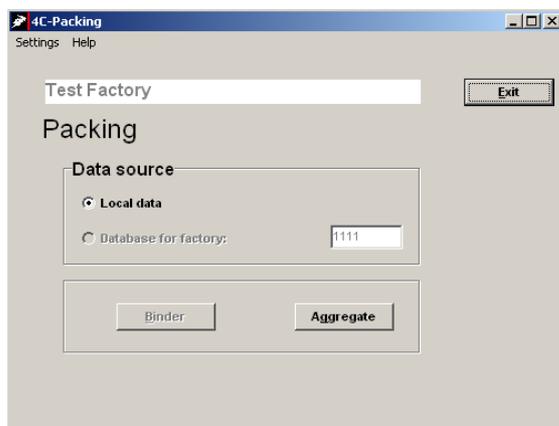
Click the "Aggregate"-button to start using 4C-Packing.

Click "Settings" to modify:
- the language (English or Danish)
- the name of your "Test Factory"
- the sieve sizes used

Click "Help" to see information about your version of 4C-Packing

Figure 3: Active window when "Settings" and "sieve sieves" have been chosen.
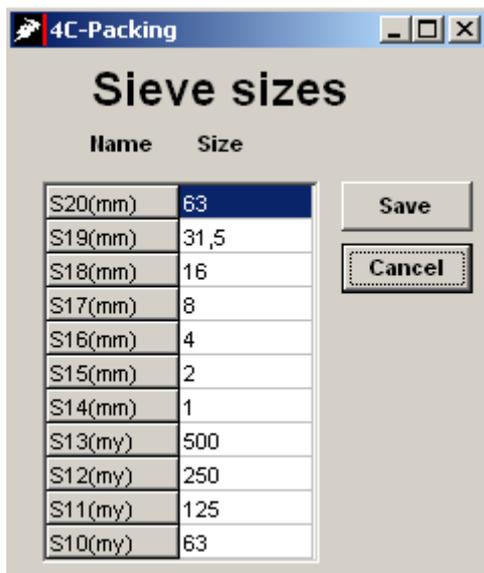
The sieve sizes can be changed here, however, this is NOT recommended. Should your grading curves contain intermediate sizes these can typically be omitted without loss of essential accuracy in the 4C-Packing calculations

Notice that the sizes of the four last sieves are provided in microns.

Click the "Save"-button to save changes to the sieve sizes used in 4C-Packing. The change will be global and apply to all materials in the database, i.e. all materials have the same sieve sizes associated.

3.   Main user-interface

The use of 4C-Packing takes place almost solely in a single window - the main user-interface - as shown in Figure 4. The interface consists of two main areas the "Database" area below the red line and the "Calculations" area above the red line.
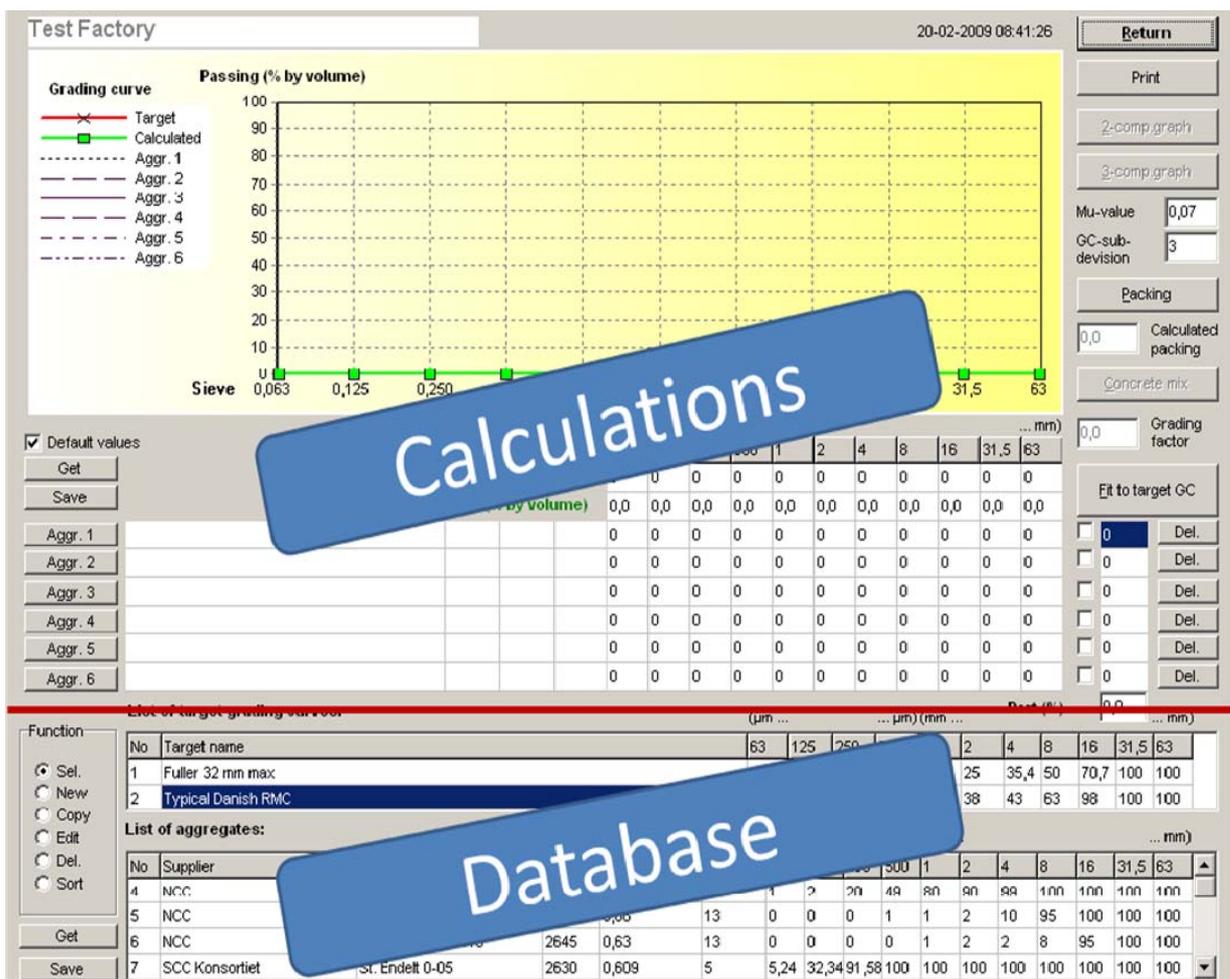
3.1   The "Database" area

The "Database" area consists of the "list of target grading curves" and the "list of aggregates". Both lists are edited using the "Function" area to their left, which contains the following options:

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- *"Sel."* (select) is marked automatically when materials are selected for the calculation area.
- Choose *"New"* and then click on any line in the "list of aggregates" to create a new line at the bottom of the "list of aggregates". If one or more aggregates are selected in the "Calculations" area, a new material with properties reflecting the active combination will be created, i.e. the grading curve will be as shown in "Calculated passing" (green curve), and the density, eigen-packing and unit cost will be the weighted average.
- Choose *"Copy"* and then click on a line in the "list of aggregates" to copy that line.
- Choose *"Del."* (delete) and then click on the a line in the "list of aggregates" to delete this line.
- Choose *"Sort"* and then click on a column in the "list of aggregates" to sort the list based on content of the column clicked. The sorting is alphabetical in all columns, and numbers are sorted first according to the first digit from the left, then according to the second digit, etc.

The changes made to the "list of aggregates" and/or "the "list of target grading curves" are saved by pressing the "Save"-button in the lower left hand corner. The "Get"-button are used to reload the database files. This is sometimes useful if on-screen changes have been made that the user does not want to retain.

The information in the "list of aggregates" and the "list of target grading curves" are saved as LokData.txt and TargetData.txt to the directory that 4C-Packing was installed under.

3.2 The "Calculations" area

The "Calculations" area is where the majority of the daily use of 4C-Packing takes place. It contains an area for graphical display of grading curves, an area for displaying materials selected from the "list of aggregates" as well as a number of buttons of the right hand side for activating calculations and displaying additional windows.

3.3 Selecting aggregates for calculation

Aggregates are selected for calculations by pressing one of the buttons "Aggr. 1" – "Aggr. 6" followed by clicking with the mouse on one of the materials in the "list of aggregates" (Figure 5).

When an aggregate has been selected to the "Calculations" area, a mark shall be placed to the right of the line in order for the programme to include it in the calculations. When the mark is placed next to a material, its size distribution curve is displayed in the graph above (Figure 6).

When removing the mark the grading curve is no longer displayed and the aggregate is not part of the calculations. Press the "Del."-button to delete the selected aggregate from the "Calculations" area.

Figure 5. Selecting an aggregate to the calculation area.

Figure 6. "Activating" an aggregate so that it is included in the calculations.

3.4 Selecting target grading curve

To select a target grading curve click on the curve data in the "list of target grading curves". This will send the data to the calculation area, where the data is displayed the red line in the diagram and in red as "Target passing (% by volume)".
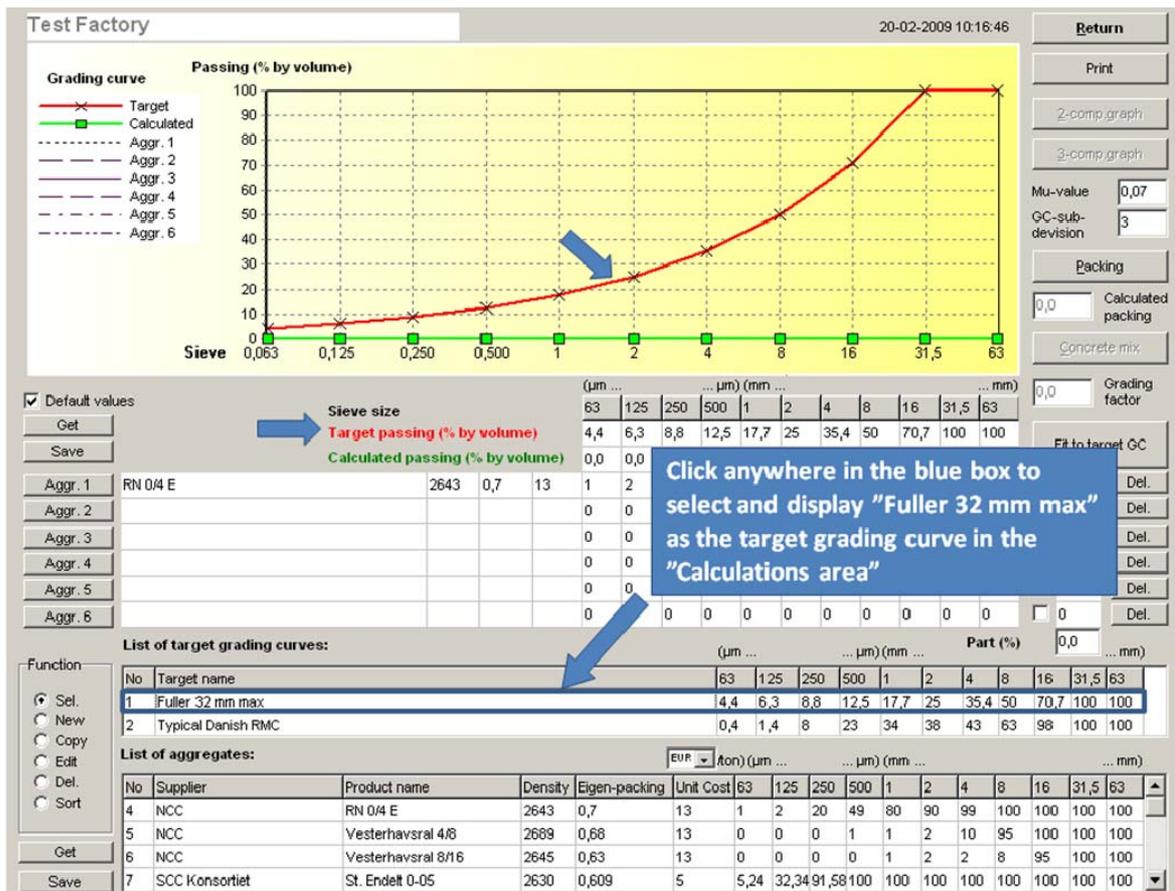

Figure 7. "Activating" an aggregate so that it is included in the calculations.

3.5 Calculating and displaying combined grading curves

To the right of the marking, the user can add the % by volume that the individual aggregate constitute of the chosen combination of aggregates. The combined grading curve of the chosen aggregate combination is shown in the line "Calculated passing (% by volume)" that is also displayed in the graph as the green line (Figure 8).
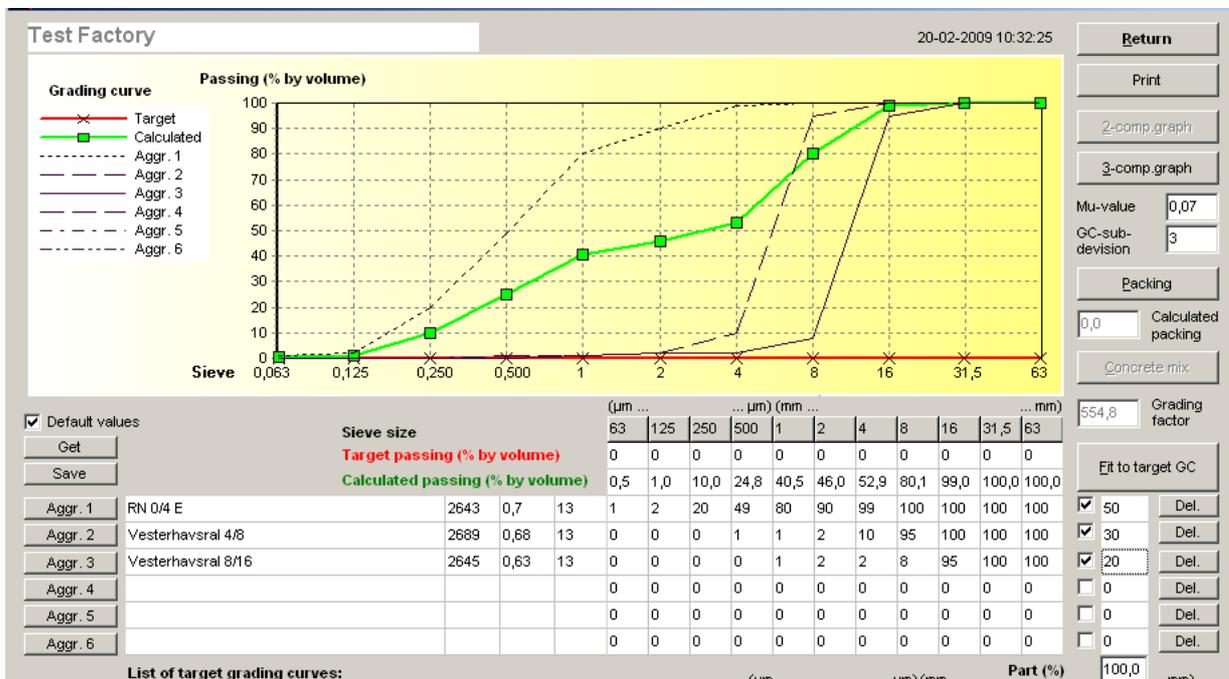
Figure 8. Combined grading curve and passing % (green curve and numbers) of the 50:30:20 % by volume combination of RN 0/4 E, Vesterhavsral 4/8 and Vesterhavsral 8/16.

3.6   Fitting selected materials to a target grading curve

Select the materials in the calculation area that are to be included in the calculation (it is not necessary to fill in the spaces with percentages by volume).

Select a target grading curve as described under 3.2.2.

Press the "Fit to target GC"-button. The best fit combination of the selected aggregates will be shown in percentage by volume, and the best fit grading curve will be shown in green as "Calculated passing (% by volume)" and as a green line in the graph (Figure 9).
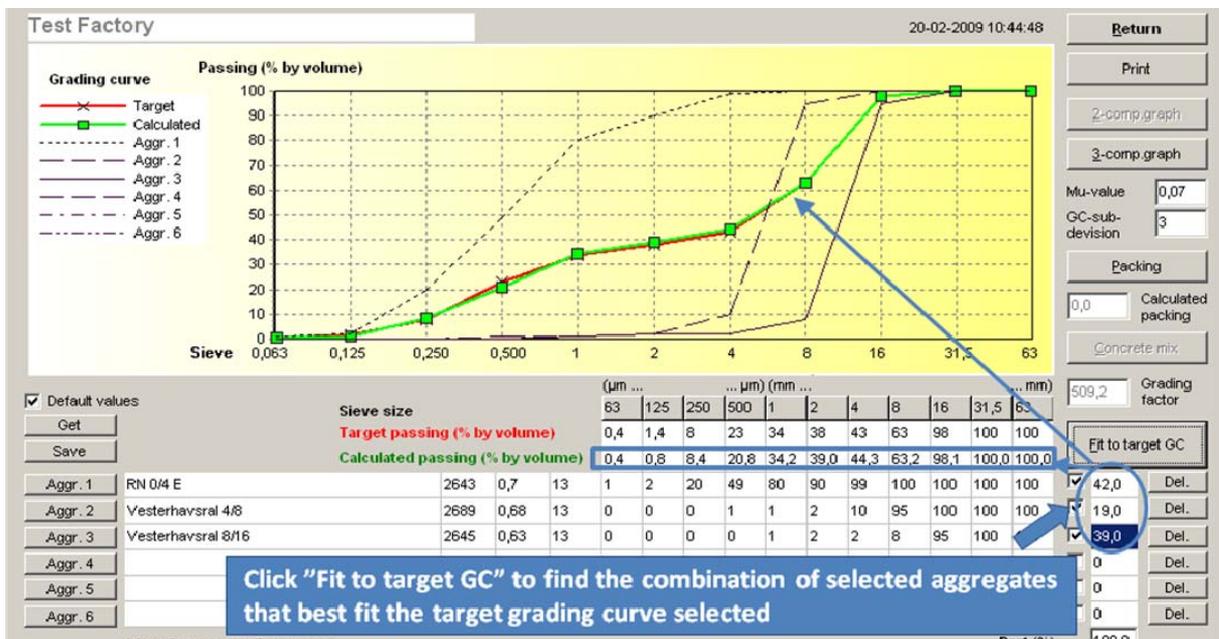
Figure 9. The best fit to the selected target grading curve is the 42:19:39 % by volume combination of RN 0/4 E, Vesterhavsral 4/8 and Vesterhavsral 8/16. The corresponding grading curve is shown as the "Calculated passing (% by volume)" and as the green line on the graph.

3.7   Packing calculation

The packing of a particular combination of selected aggregates can be found by pressing the"Packing"-button, and the result will be shown in the "Calculated packing"-field (Figure 10).
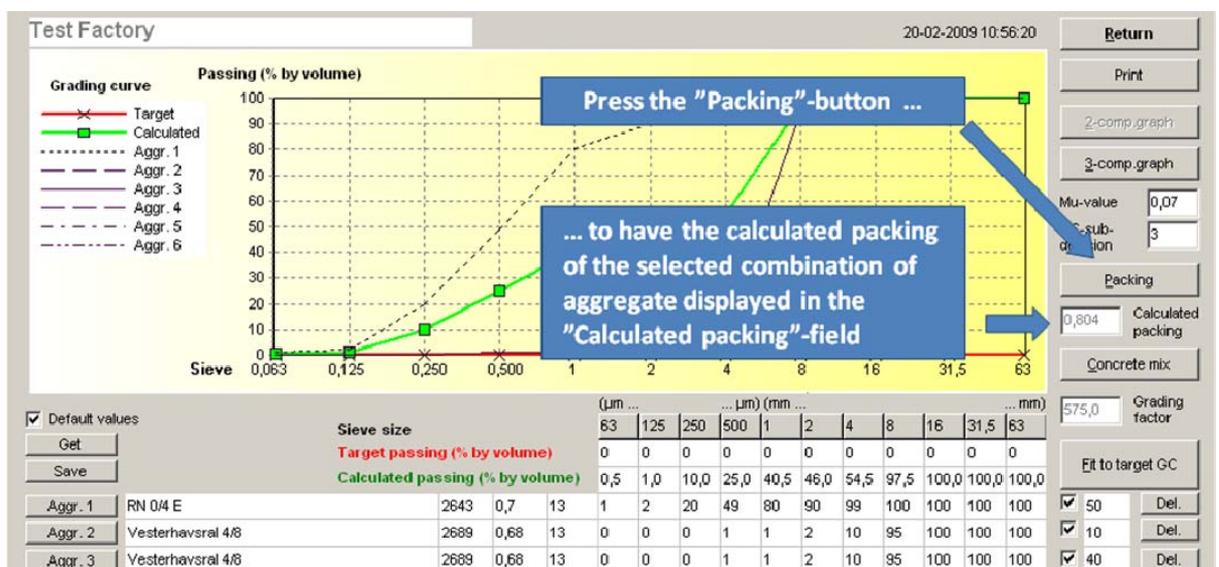
Figure 10. The packing of the 50:10:40 % by volume combination of RN 0/4 E, Vesterhavsral

4/8 and Vesterhavsral 8/16 is found by pressing the "Packing"-button. The result is displayed in the "Calculated packing"-field.

3.8   Packing diagrams

Two types of packing diagrams can be displayed, binary diagrams (two aggregates) and ternary diagrams (three aggregates).

3.9   Binary packing diagram

To bring up the binary packing diagram only two aggregates must be selected. Press the "2-comp. graph"-button to open a new window with the binary packing diagram (Figure 11).

Use the mouse to move the dashed vertical line that represents the % by volume of one aggregate at the top and of the other aggregate at the bottom. The packing representing the position of the vertical line is calculated simultaneously with movement of the line. Left click on the mouse to select (lock) a particular combination of the two aggregates.

Press the "Return"-button (upper right hand corner) to transfer the selected (locked) combination to the "Calculations" area of the main window. The % by volume and the packing are transferred, and the combined grading curve is calculated and displayed.
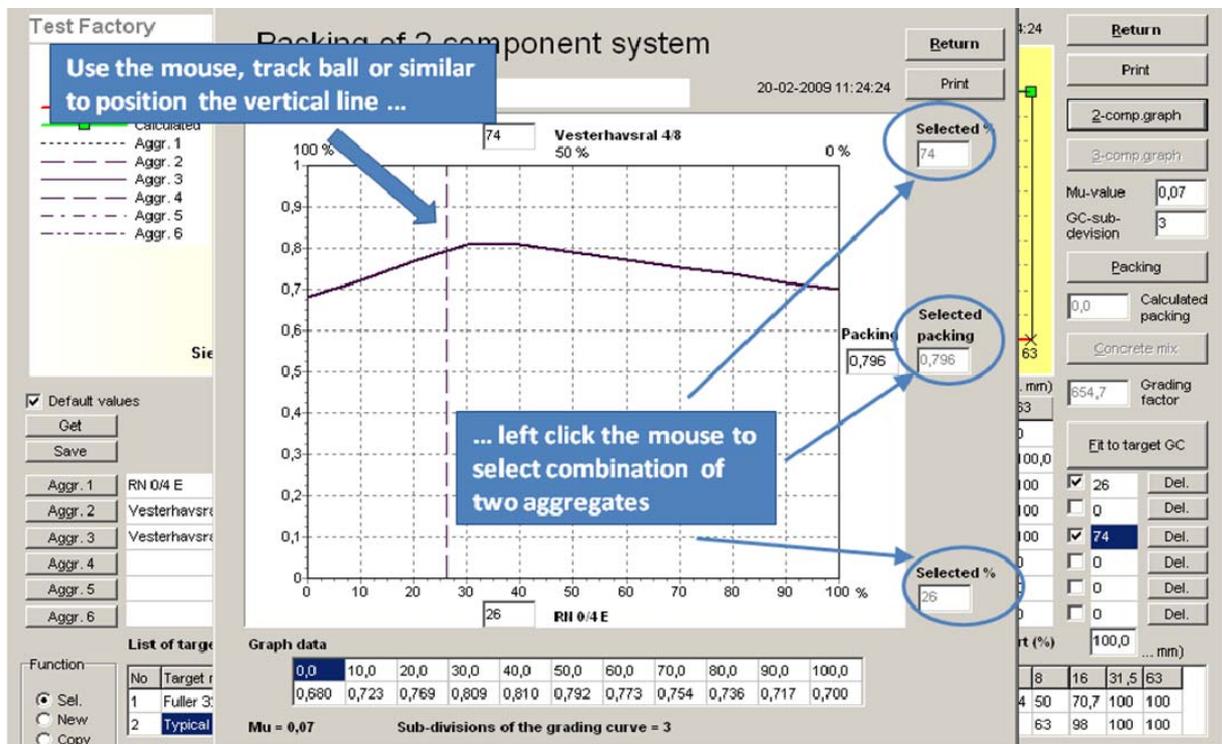
Figure 11. The window with the binary (2-component) packing diagram. Press the "Return"-bottom to transfer selected (locked) combination to the "Calculations" area of the main window.

The binary packing diagram can be printed by pressing the "Print"-button.

Be aware that the diagram only shows straight lines between the points separated by 10% by volume, i.e. the maximum can be significantly higher than indicated by the curve shown.

3.10   Ternary packing diagram

To bring up the ternary packing diagram only three aggregates must be selected. Press the "3-comp. graph"-button to open a new window with the ternary packing diagram (Figure 12). The diagram will contain a green and a red dot representing maximum packing and selected packing respectively.

Use the mouse to move the cursor around in the diagram. The position of the cursor represents an aggregate combination, of which the % by volume is shown next to each axis. The packing representing the position of the cursor is calculated simultaneously with movement of the cursor. Left click on the mouse to select (lock) a particular combination of the three aggregates.

Press the "Return"-button (upper right hand corner) to transfer the selected (locked) combination to the "Calculations" area of the main window. The % by volume and the packing are transferred, and the combined grading curve is calculated and displayed.
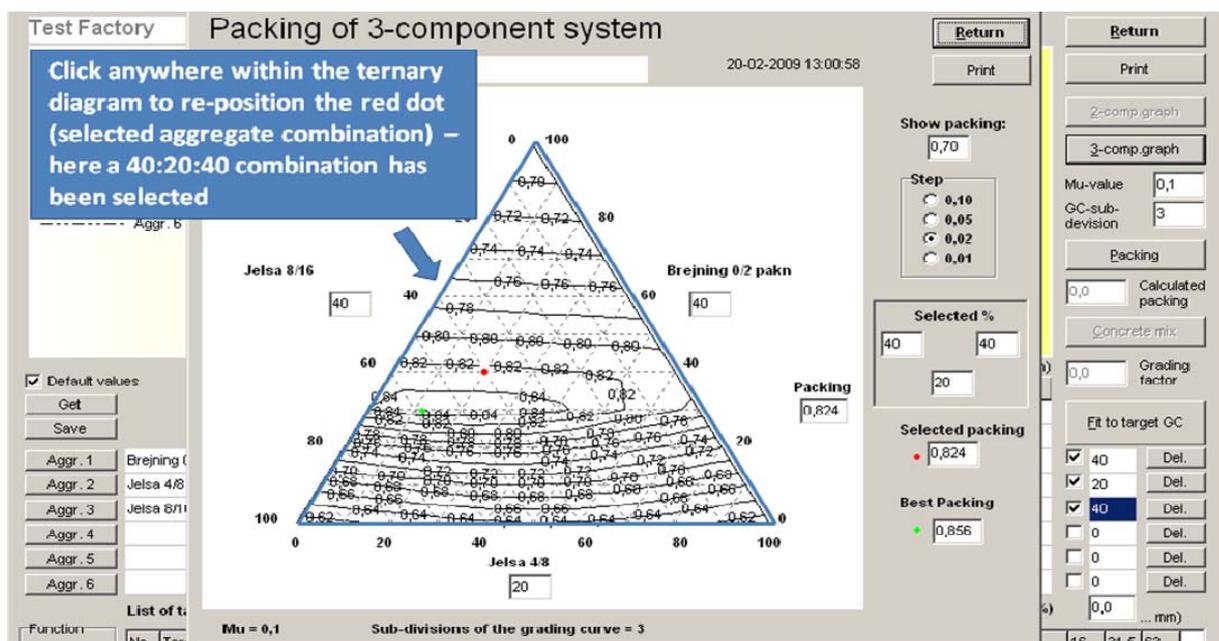

Figure 12. The window with the ternary (3-component) packing diagram. Press the "Return"-bottom to transfer selected (locked) combination to the "Calculations" area of the main window. The green dot is fixed representing maximum packing.

The value of the "Step" parameter defines the separation of the iso-packing lines. At a value of 0.02 as in Figure 12 the lines shown are 0.84; 0.82; 0.80; etc, but if the value was 0.05 the values shown would be 0.85; 0.80; 0.75; etc. The "Show packing" box is used to set the reference point for the iso-packing lines. If the value in Figure 12 was changed to 0.71 then the iso-lines showed would be 0.71, 0.73, 0.75, etc.

3.11 Packing of more than three materials

It is not possible to show graphically the packing of more than three materials. However, it is possible to calculate the packing of more than three materials by specifying a weight fraction for each material in the "Calculations" area and then pressing on the "Packing"-button (remember that each material must be marked with a checkmark).

"Pseudo" aggregates can be created as any combination of selected aggregates. Figure 13 illustrates how a 50:50 combination of two materials is obtained in the "List of aggregates". Select the two aggregates to be combined to the "Calculations" area. Choose 50 % by volume of each aggregate. Select the "New" function next to the "List of aggregates" and click on any line in the "List of aggregate" to create a new line with the properties of 50:50 combination of

the two select aggregates. The 50:50 combination can now be used as a single aggregate in e.g. binary and ternary diagrams.
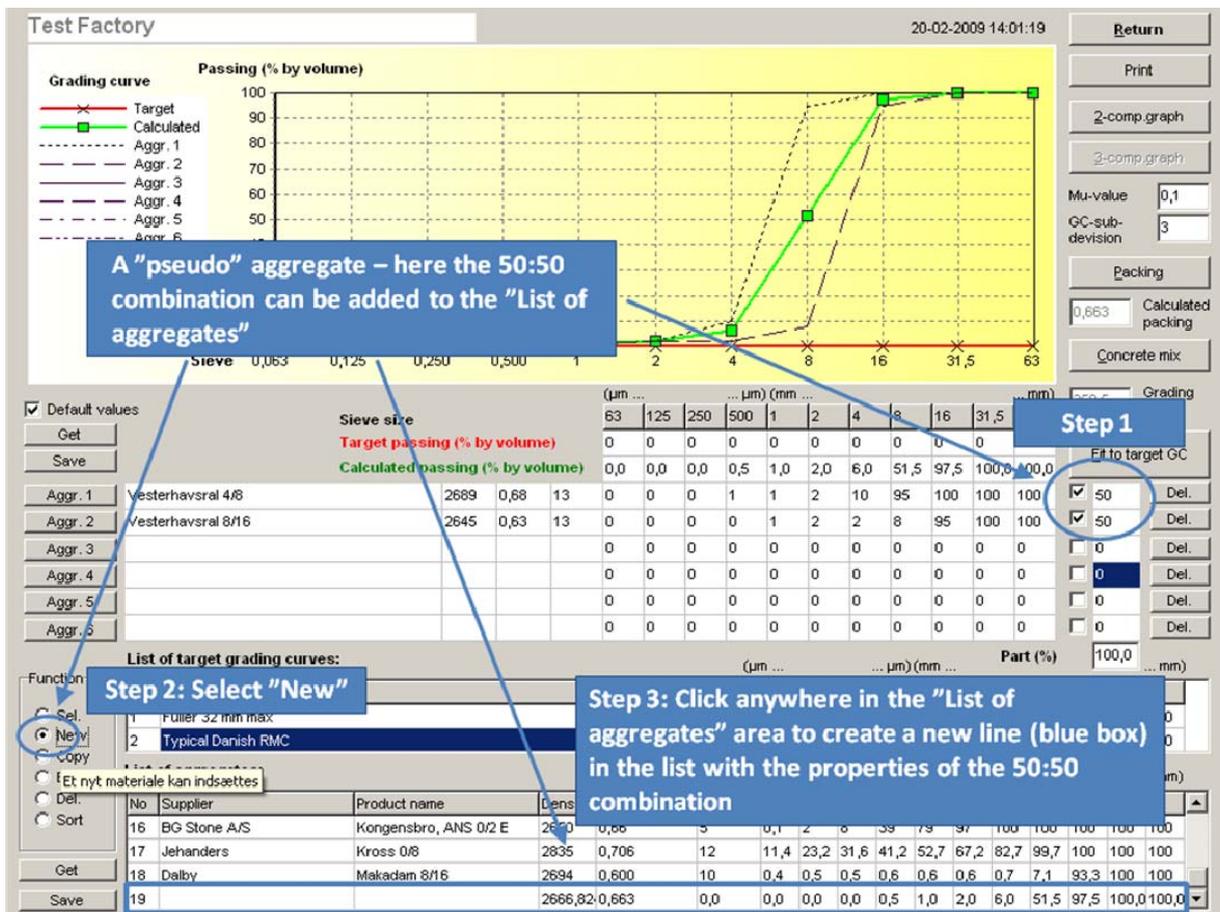
Figure 13. A 50:50 combination of Vesterhavsral 4/8 and Vesterhavsral 8/16 is created and can be used as a single aggregate in further packing studies.

3.12   Packing calculation parameters

In addition to material data for each aggregate, 4C-Packing uses two calculation parameters: "GC-subdivision" and the so-called "Mu-value".

GC-subdivision
In the calculations, each of the defined sieve jumps is subdivided into a number of smaller jumps, specified in the box "GC-subdivision" (distribution curve subdivision) in the upper right corner of the screen picture. Increasing the number of subdivisions improves the accuracy of the packing calculation, but increases the calculation time. Normally a "GC-subdivision" of 3 will be sufficient; it means that each sieve jump in the distribution curve is subdivided into 3 equal size intervals, on which the calculation is then based.

For practical purposes the specified value of the GC-subdivision has limited influence on the results of the packing calculations. Figure 14 shows the same ternary diagram calculated based on a fixed "Mu-value" of 0.07 and "GC-subdivision" values of 3, 5, 10 and 20. As can be seen only very minor changes exist between the packing diagrams.
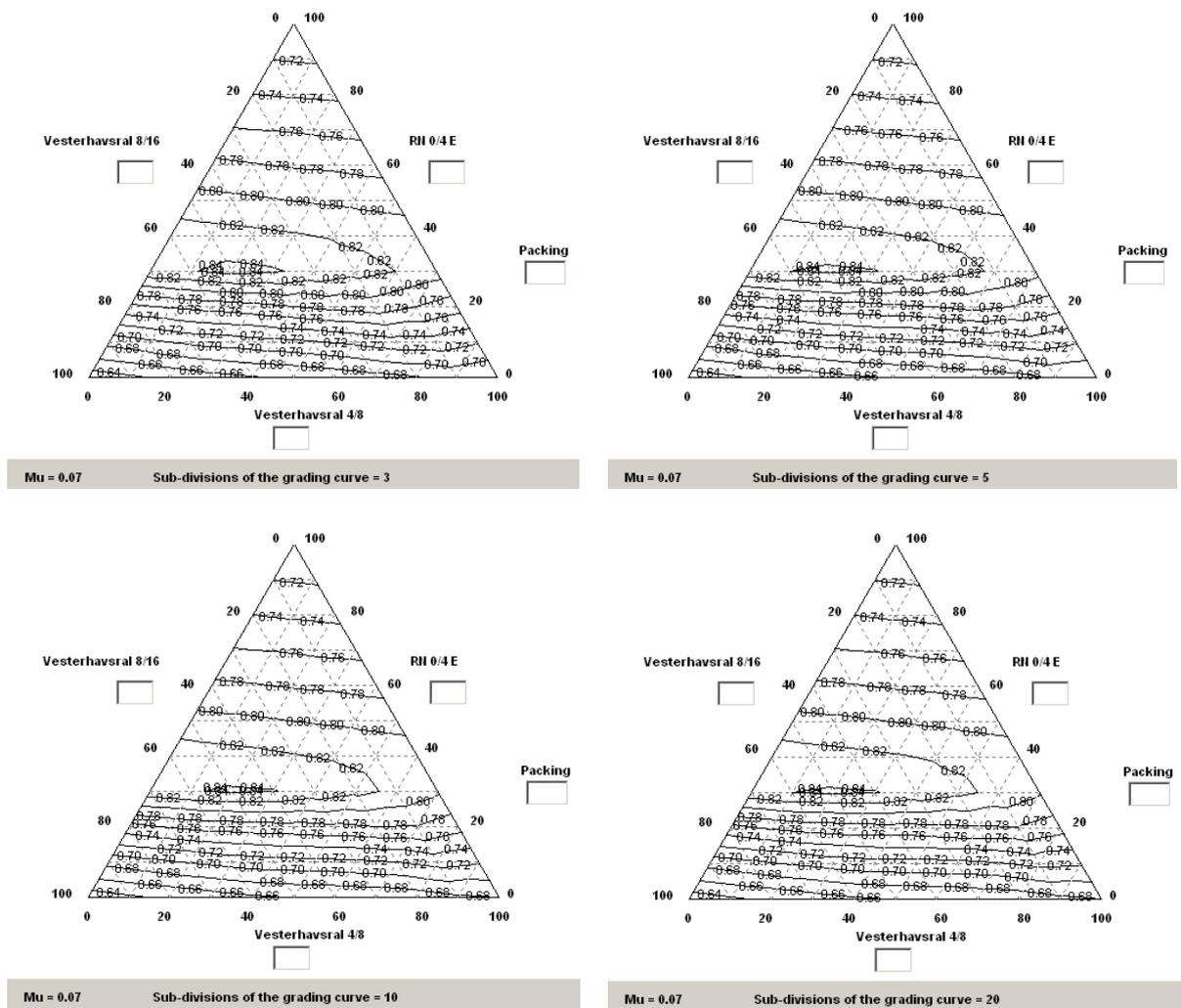
Figure 14. The influence of the parameter "GC-subdivision" on the ternary diagram. Only very minor differences are observed between the diagrams representing GC-subdivisions of 3, 5, 10 and 20 as indicated on the Figure. The "Mu-value" was constant at 0.07.

Mu-value
When small and large particles are packed, the small particles will often be unable to fill the voids between the large particles without disturbing their packing. This "loosening-effect" is quantified by the so-called "Mu-value", which indicates the maximum size ratio between the two particle types where no interaction (loosening) takes place, i.e. there is just sufficient voids space between the large particles to accommodate the small particles.

As the "Mu-value" is a relative value, it is independent of absolute sizes. For a given material type the "Mu-value" should therefore be the same regardless of whether the material is sand or aggregate. The "Mu-value" will normally be in the range 0.07 – 0.13 /2/.

In 4C-Packing the "Mu-value" is specified by the user in the "Mu-value" box in the upper right hand corner of main window.

For practical purposes the specified value of the "Mu-value" has some influence on the results of the packing calculations. Figure 15 shows the same ternary diagram calculated based on a fixed "GC-subdivision" of 3 and "Mu-value" values of 0.04, 0.07, 0.13, 0.20.
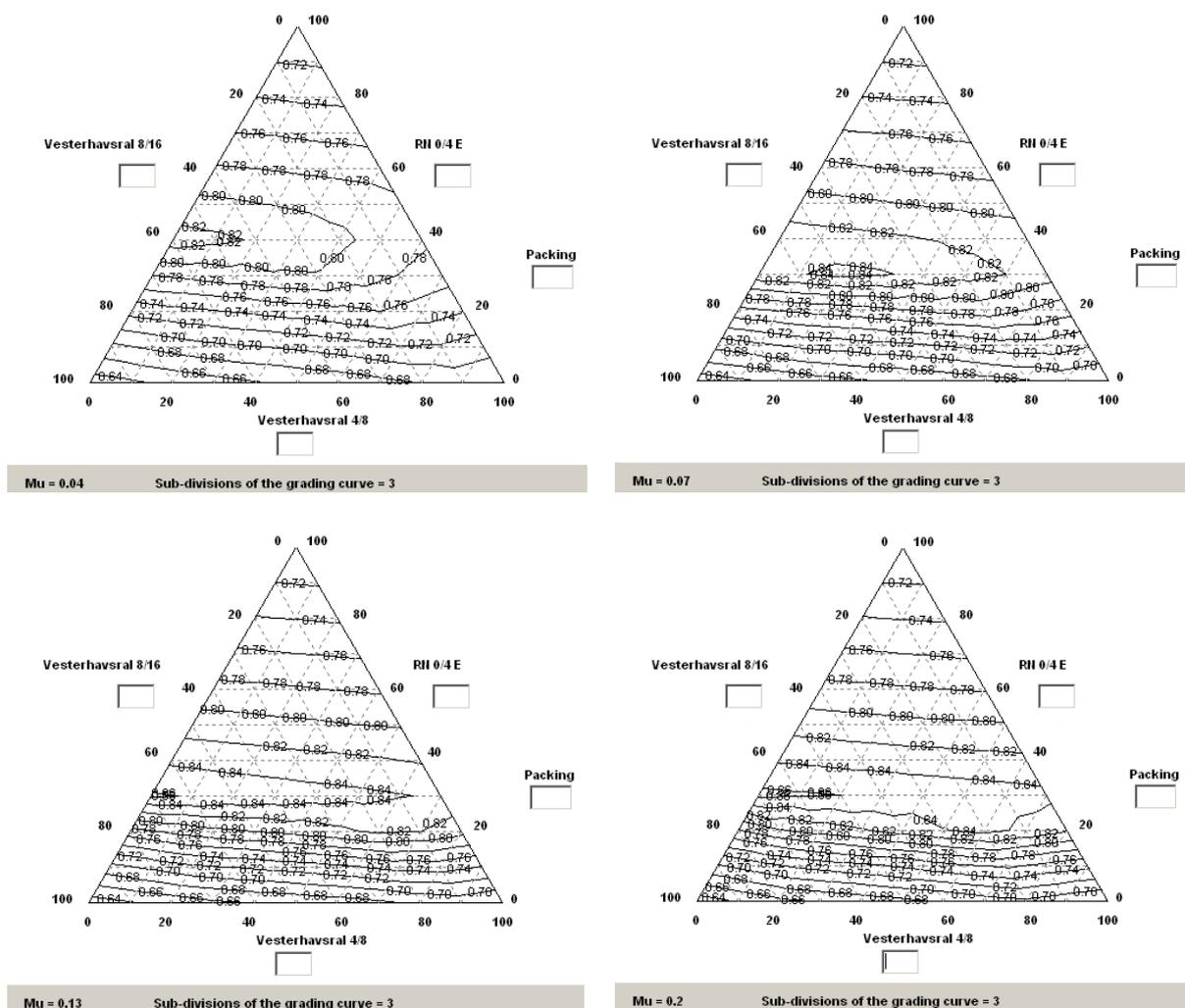

Figure 15. The influence of the parameter "Mu-value" on the ternary diagram. Only very minor differences are observed between the diagrams representing Mu-values of 0.04, 0.07, 0.13 and 0.20 as indicated on the Figure. The "GC-subdivion" was constant at 3.

3.13 Concrete mix design

It is possible to calculate a concrete mix design based on the chosen aggregate combination. Pressing the "Concrete-mix"-button opens a new window where the calculation takes place (Figure 16).

The input parameters for the mix design calculation are described in section 1.1, and by pressing the "Calculate"-button in the lower right hand corner of the window the concrete mix composition and cost reflecting input parameters are displayed (Figure 17).

If a printer is connected to the PC the calculated mix design can be printed by pressing the "Print"-button.

Figure 16. The mix design window is displayed by pressing the "Concrete mix"-button.

Figure 17. Calculation of concrete mix design based on a 50:10:40 % by volume combination of RN 0/4 E, Vesterhavsral 4/8 and Vesterhavsral 8/16. Add values of "Excess paste", "w/c-ratio", "Air volume", "Cement density" and "Cement cost" in the respective boxes. Then press the "Calculate"-button to get the corresponding concrete composition and its cost.

4. References

A more detailed description of the theoretical basis of packing calculations for a combination of materials can be found in the following literature:

1. *T. Stovall, F. de Larrard and M. Buil:*
    "Linear Packing Density Model of Grain Mixtures"
    Powder Technology, 48 (1986) 1-12

2. *Mette Glavind, Ingolf Sørensen og Esben Thygesen:*
    "Pakningsberegninger som hjælpemiddel ved betonproportionering"
    Beton-Teknik 2/11/1999

3. *Mette Glavind:*
    "Modificering af pakningsprogram til at kunne håndtere små partikler (cement, flyve-aske m.m.)"
    NOTAT, DTI Byggeri, 07.09.98

4. *Mette Glavind:*
    "Evaluation of the Compressive Behavior of Fiber Reinforced High Strength Concrete", Ph.D. Thesis, Serie D., No. 302, Afdelingen for Bærende Konstruktioner, Danmarks Tekniske Universitet, 1992.

Reference [2] also contains a description of a procedure for the experimental determination of the eigen-packing of a material and a guide to concrete proportioning on the basis of packing calculations.

5.   Appendix A - Installation of 4C - Packing

The programme is installed from a CD-ROM or USB-pen. Insert the media and activate the *setup.exe* file in the root and complete the installation.

Install the USB-key HASP-driver by execution the Install HASP Driver file as shown in Figure A1. Insert the USB-key in the PC. When a red light comes on in the USB-key the software is ready for use.

When a successful installation has been completed the software files will be found in the path C:\Program Files\DTI\4C-Packing (Figure A2).
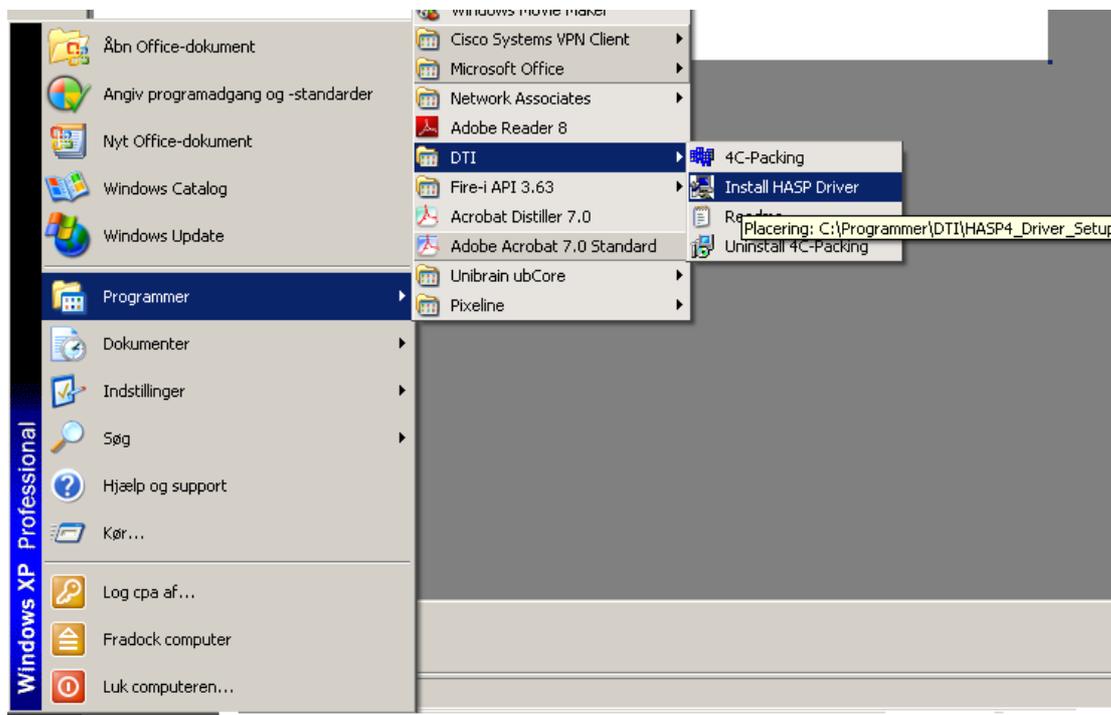

Figure A1. How to install the HASP driver – choose "Start" – "Programs" – "DTI" – "Install HASP Driver".
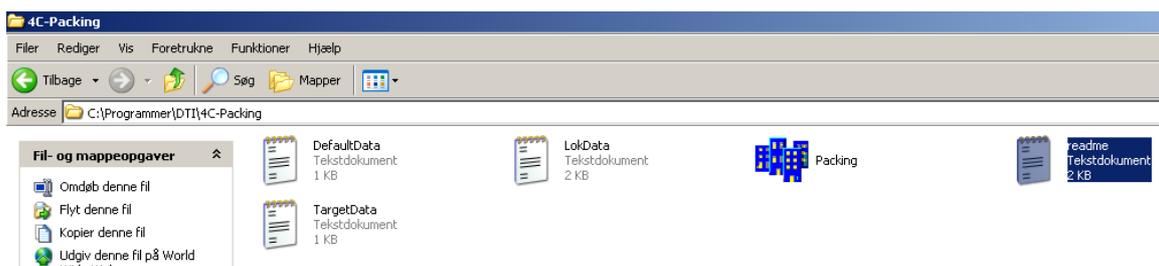
Figure A2. Location of the software on the C-drive following successful installation.

6. Appendix B - Experimental determination of eigen-packing

There is no standard method for determining the eigen-packing of aggregate.

DTI uses the following procedure to determine eigen-packing:

1. The aggregate is oven-dried at 105ºC ± 5ºC

2. A representative sample is taken.

3. The aggregate is filled into a Plexiglas container of diameter 200mm (D) and height 250mm in three approximately equal height layers. Each layer is compacted on a drop table using 80 drops of xx mm. The height (h) of the compacted aggregate in the Plexiglas cylinder is measured.

4. The container with the material is weighed (m_1).

5. The container is weighed empty (m_2).

6. The eigen-packing is then calculated as follows:

Eigen-packing = $(m_1 - m_2) / (\pi \cdot (D/2)^2 \cdot h \cdot \rho)$

where, ρ is the dry particle density of the aggregate.

Three determinations are carried out, and the eigen-packing is taken as the mean of the three results.

It is recommended to use a container of diameter at least 10 times the diameter of the largest particles and with a similar height in order to reduce the wall-effect.

The publication "Pakningsberegninger som hjælpemiddel ved betonoptimering" /2/ gives an alternative method of determining the eigen-packing of a material.

7. Appendix C - Experimental determination of "Mu-value"

The "Mu-value" is an interaction factor used in the packing programme. The "Mu-value" is the ratio of the dimension of the small to the dimension of the large particles in a 2-component system, such that there is just sufficient room between closely packed large particles to accommodate the small particles without the packing of the large particles being affected.

The "Mu-value" for spherical particles is approximately 0.2 (Stovall et al. /1/). The more the particle shape deviates from the spherical, the lower the "Mu-value". It has been found that the "Mu-value" of some Danish pit materials (sediments) is about 0.07.

The "Mu-value" is in principle independent of absolute size. This means that for a given material type, the"Mu-value" will be the same regardless of whether the material is fine or coarse aggregate.

To find whether it is necessary to determine a correct "Mu-value", a sensitivity analysis should be carried out. This can be done by calculating the packing of the materials investigated, with e.g. three values of "Mu". If the packing calculation is not sensitive (the sensitivity is evaluated according to the desired accuracy) to variations in "Mu-value", it is not necessary to determine the correct value of "Mu". Conversely, if variations in "Mu-value" results in large variations in the packing calculation, it will be necessary to determine the correct "Mu-value" of the material.

Determination of "Mu-value" can be carried out as follows. The packing is determined experimentally for all combinations of 2-component systems (a total of three combinations for three different materials), and the packing determined for the various "Mu-value"s of these 2-component systems. The "Mu-value" for which the experimental and theoretical packing agree is the correct value.