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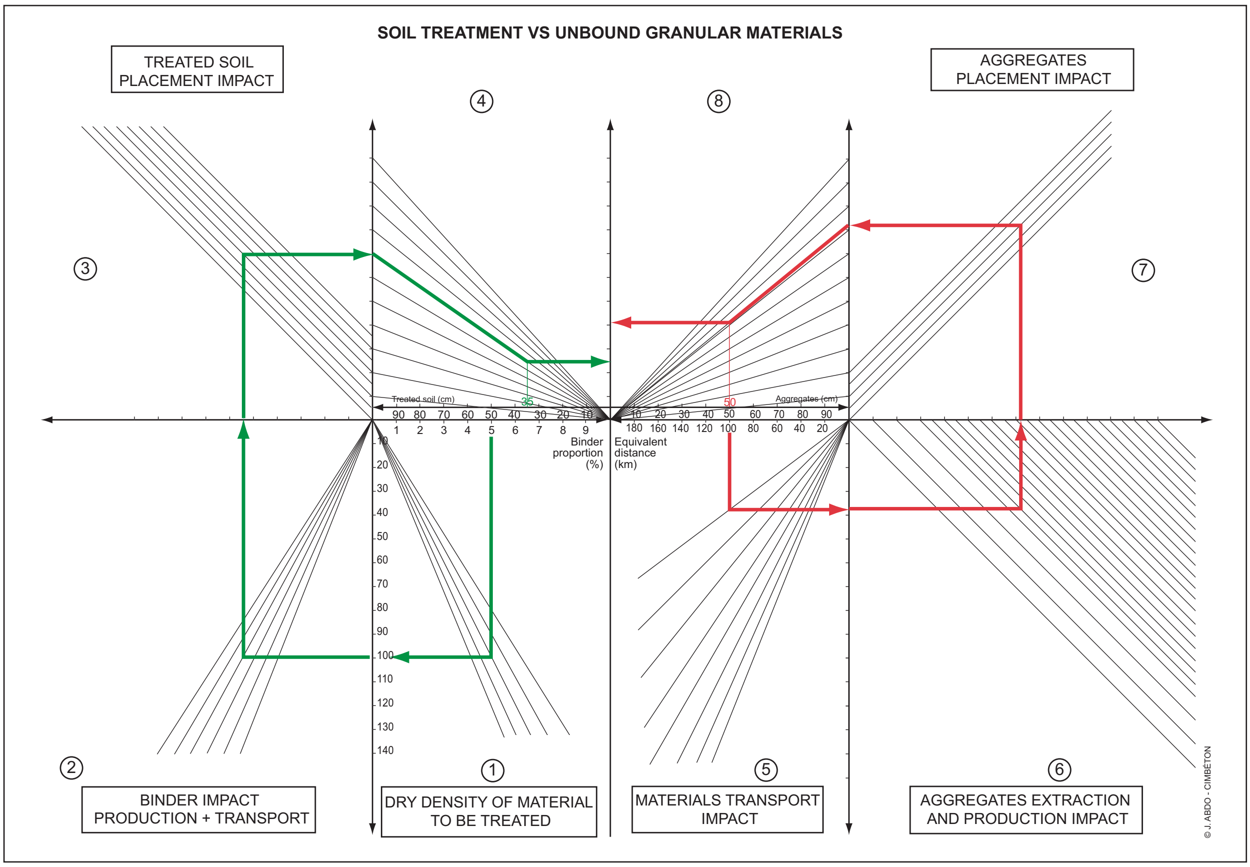
Comparative study in road engineering
Soil treatment vs Unbound granular materials

Graphic method for environmental and economic comparison



CIMbéton
CENTRE D'INFORMATION SUR LE CIMENT ET SES APPLICATIONS

COMPARATIVE STUDY IN ROAD ENGINEERING

SOIL TREATMENT VS UNBOUND GRANULAR MATERIALS

Graphic method for environmental and economic comparison

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Foreword

To build roads, motorways, airport areas or any other area development for industrial, commercial or logistical use, prior design and building of a specific road transport platform of minimum bearing capacity is necessary, allowing construction of the actual pavement structure.

Building the specific platform, which relates to road earthworks, consists in carrying out levelling works (cuttings and embankments) and building a structural layer referred to as «capping layer».

Cutting, embankment and capping layer works may be performed using one of the two following techniques:

- **The technique of unbound granular materials,** which consists in using granular materials from gravel pits or quarries,

- **The technique of in situ Soil treatment with hydraulic binders,** which consists in adding value to natural soils (existing on the construction site) by mixing them with hydraulic binder and water.

These two techniques have advantages and drawbacks, both at economic and environmental level.

The technique of unbound granular materials, that uses granular materials whose extraction and production have low economic and environmental impact, may be hindered by the impact generated by:

- transport of aggregates (a heavy bulk product), when the distance between the quarry and the construction site exceeds a certain threshold.

- transport of surplus soil between the construction site and the tip.

The technique of *in situ* Soil treatment with hydraulic binders requires the use of a hydraulic binder whose production has a non-negligible economic and environmental impact. However, this binder is used in low proportion and the quantities produced and transported are small compared to the quantities of unbound granular materials.

Therefore, depending on the context of each project (distance between quarry and construction site, construction site and tip, binder proportion, distance between binder plant and construction site), one of these two techniques may prove to be economically and/or environmentally more valuable.

This manual, entitled «Comparative study in road engineering - Soil treatment vs Unbound granular materials» provides a graphical method that helps determine and compare economic or environmental indicators (Energy and CO_2).

It has a dual advantage:

- it allows users to choose the values of parameters at each stage of the study, depending on the local data of their projects,

- it allows users to quickly and visually assess and compare, in a cumulative progression, which of the two techniques, Soil Treatment or Unbound granular materials, is most appropriate, economically and/or environmentally.

It takes into account the production impact (binder, aggregates), transport impact (binder, aggregates, surplus soil) and materials placement impact (Treated soil, Unbound granular materials).
It does not take into account some factors which would have given advantage to Treated soil technique : the cost of tipping, the cost to rehabilitate local road networks which would be damaged by the traffic generated by the construction site (materials transport) and the social cost, related to this traffic (risks of accidents, disturbances,...).

In this document you will find a series of diagrams that may be photocopied, as often as needed, for users to carry out specific studies.

The Economic diagram is adapted from the abacus published in appendix 4 of the technical guide «Soil treatment with lime and hydraulic binders» (GTS – SETRA/LCPC – 2000). The Environmental diagrams (Energy and CO_2) were made using the same method but are previously unpublished.

We feel sure that the methodology that we have elaborated will help you efficiently make the choices you need for your road earthworks projects.

Joseph ABDO
Road manager - CIMBÉTON

Contents

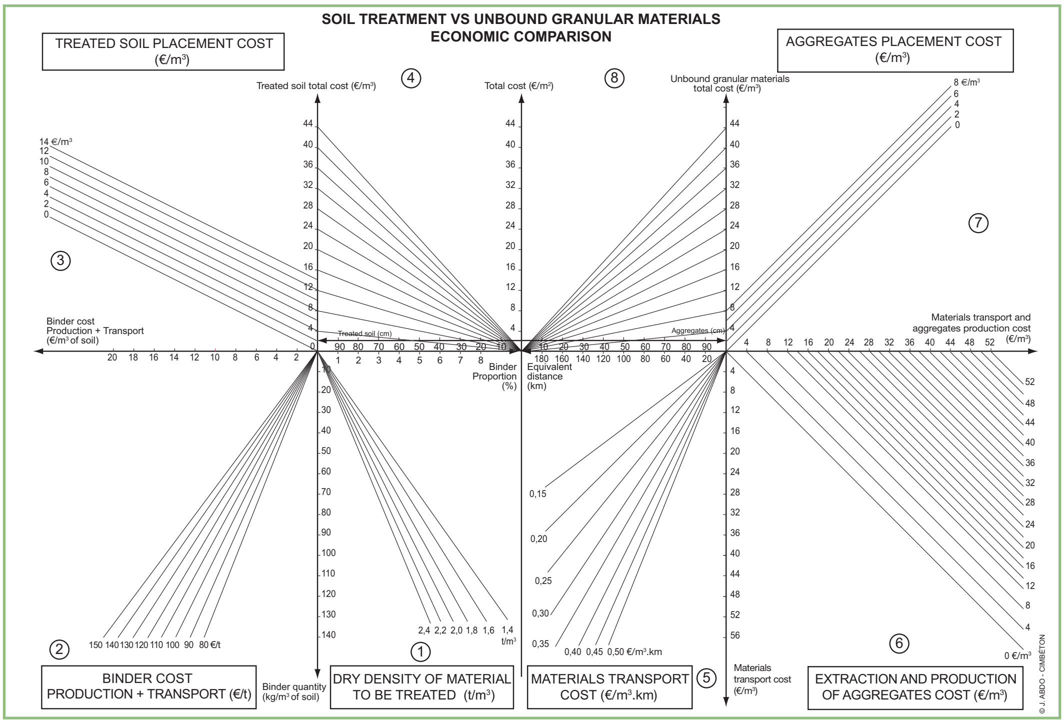
Chapter 1

Fundamental principles of the graphic comparison method

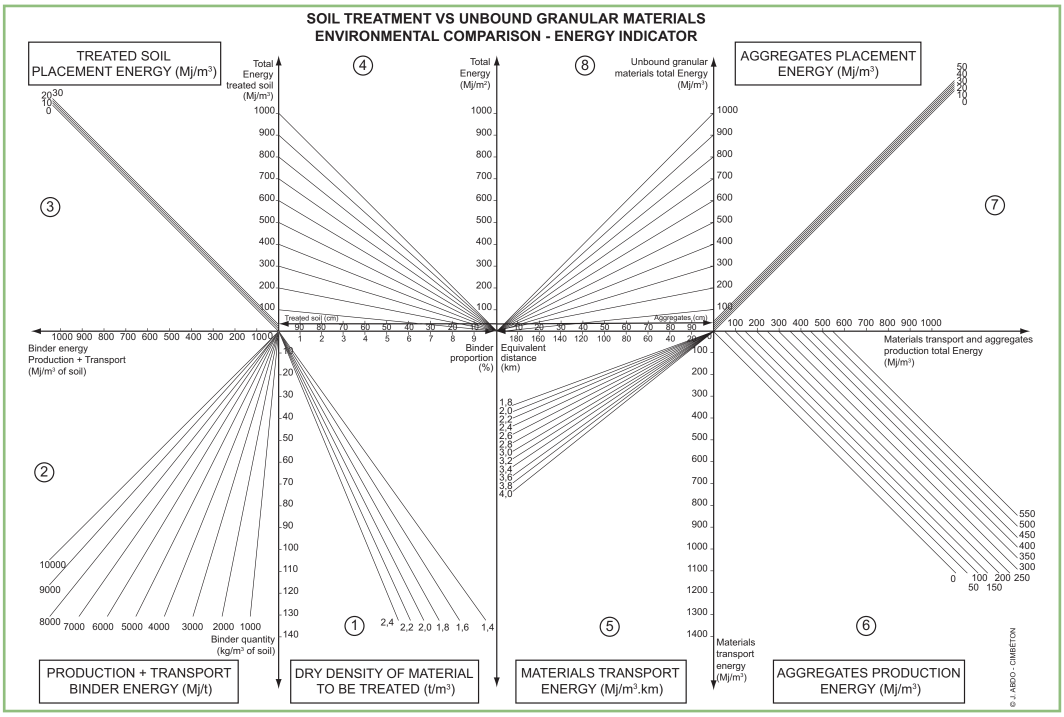
1.1 - The 3 comparative graphs

This document includes 3 different graphs.

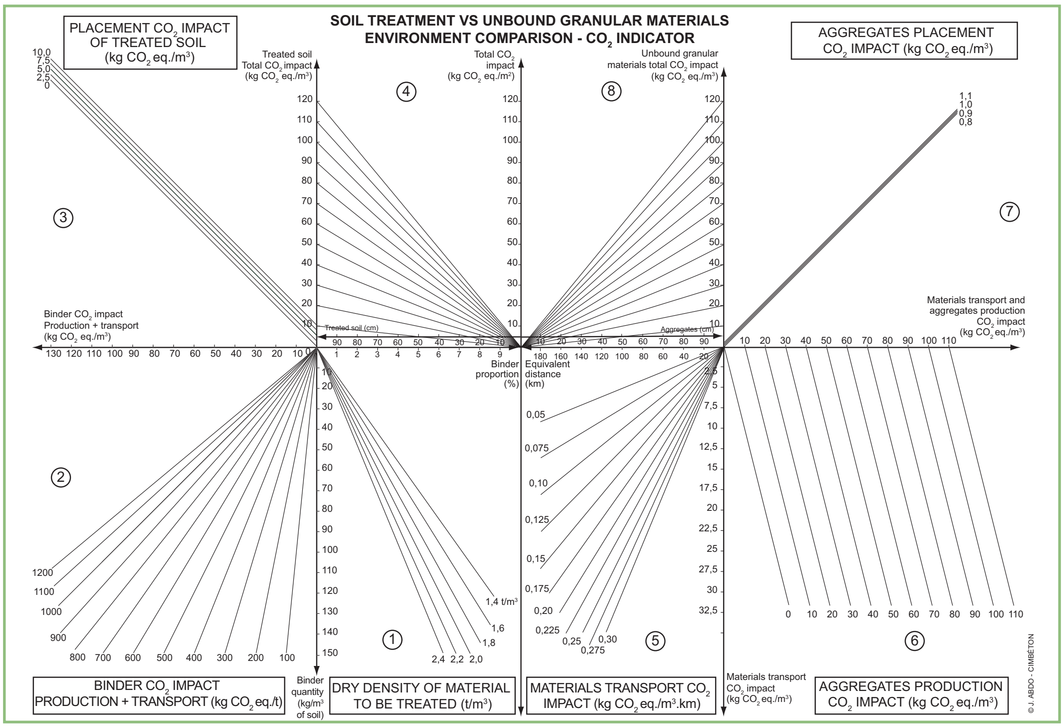
1.1.1 - Economic Comparison Graph



1.1.2 - Environmental Comparison Graph - Energy Indicator

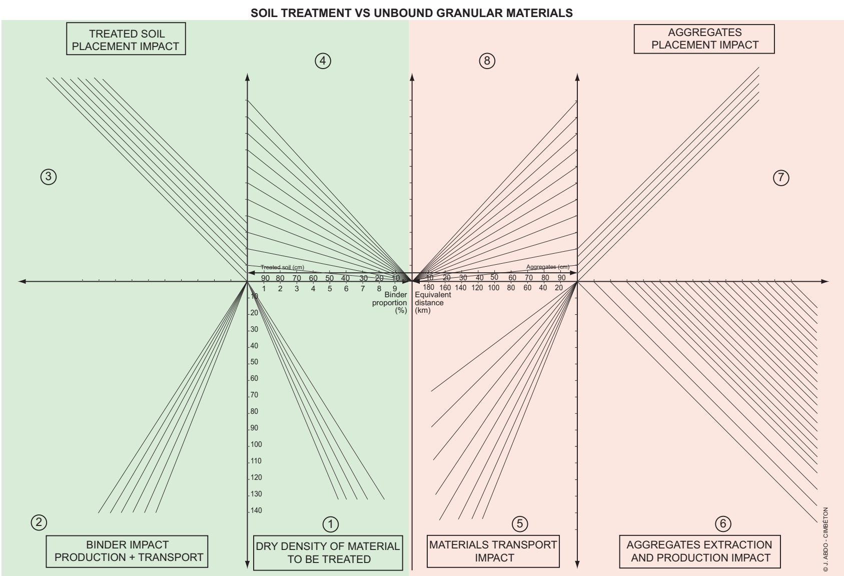


1.1.3 - Environmental / CO_2 Indicator Comparison Graph



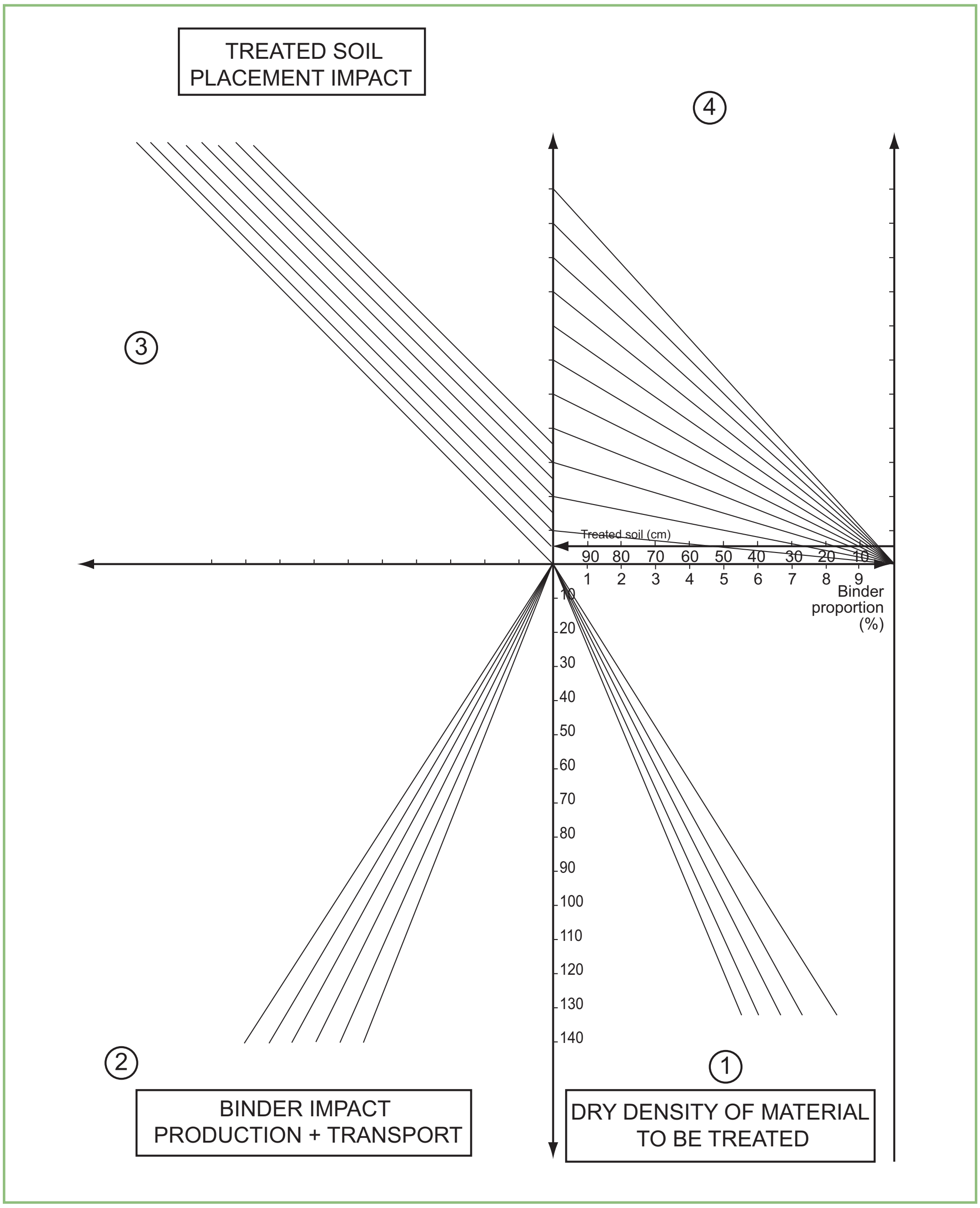
1.2 - Division into 2 comparison zones

Each of the 3 graphs presented in this document is divided into 2 zones (Zone 1 in green on the left and Zone 2 in red on the right), where each zone represents a specific technique and is itself divided into 4 quadrants.



1.2.1 - Zone 1

It covers the left half of the graphs and relates to the *in situ* Treatment technique of materials.

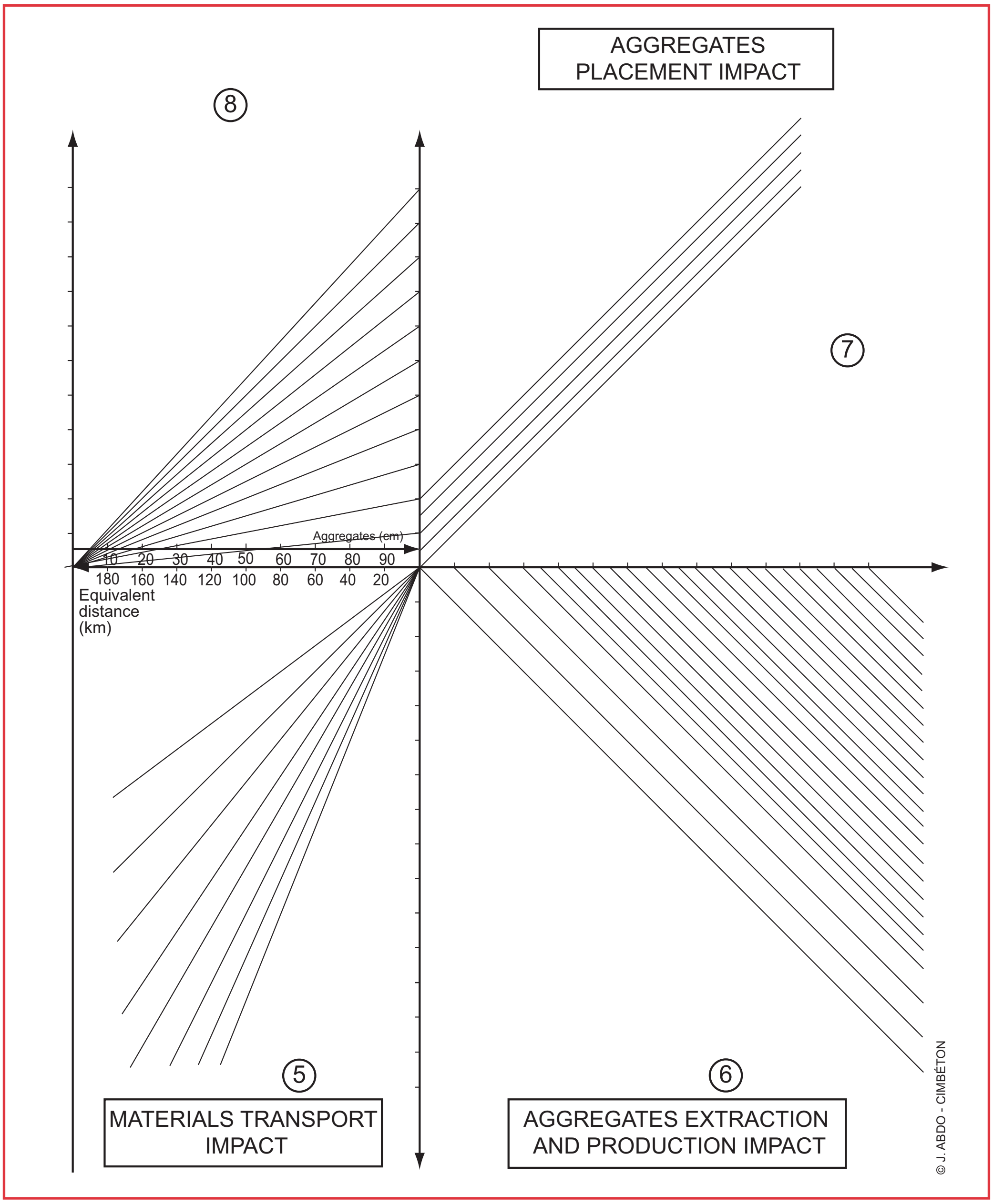


In this zone, the specific and main parameter is the binder that needs to be produced, transported to the construction site where the placement process (spreading in small quantities in the order of 30 kg/m², mixing, spraying, levelling, compaction, curing) is carried through.
This enables to obtain a material treated for use in embankments (impact evaluated per m³ of treated soil) or in capping layers (impact evaluated per m² of treated soil).

In Zone 1, it is thus obvious that the comparison study should start with binder proportioning.

1.2.2 - Zone 2

It covers the right half of the graphs and relates to the technique of Unbound granular materials.



In this zone, the main parameter is the equivalent distance, or quarry-site distance + site-tip distance. Indeed the Unbound granular materials technique requires, in addition to extraction, production and placement (levelling, spraying, compaction) of aggregates, the transport of heavy material for use in significant thickness for embankments and in large quantities (on the basis of one ton per m^2) for a capping layer, and especially tipping of surplus soil.

In Zone 2, it is thus obvious that the comparison study should start with the equivalent distance.

1.3 - Study of Zone 1 – Soil treatment

This zone is divided into 4 quadrants numbered 1, 2, 3 and 4. Here are the main characteristics of each of these quadrants.

1.3.1 - Quadrant 1

It helps calculate the quantity of binder required per m³ of soil to reach the performances required for the material treated, within the scope of the project under study.

In this quadrant we see a family of straight lines (going through the origin) that represent various dry densities, corresponding to a wide range of materials that can be found in nature (figure 1).

Thus, for a given project, when the dry density of the soil and the binder proportioning are known, we simply draw a descending vertical line going from the binder proportion digit to the intersection with the straight line of the dry density chosen: the binder quantity per m³ of soil necessary for Soil treatment can then be read directly on the vertical axis of this Quadrant.

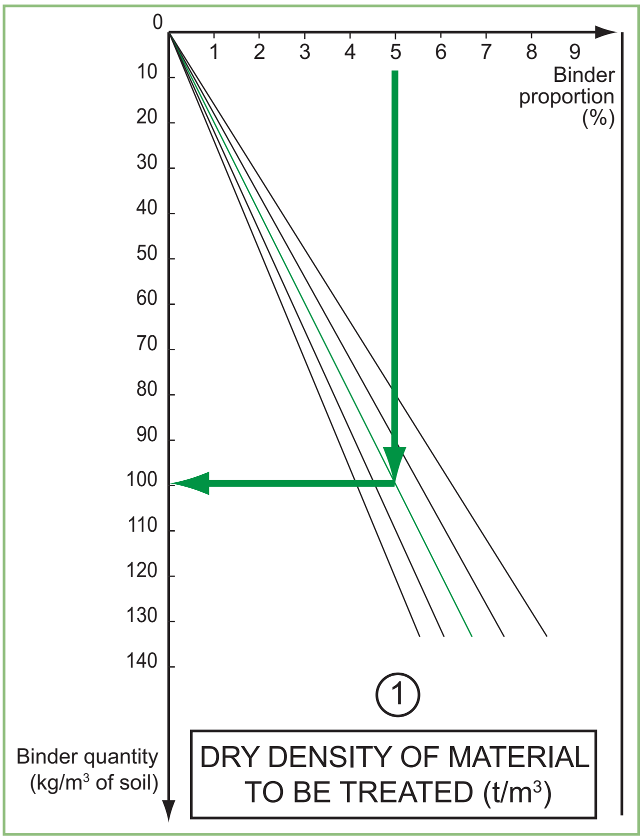


Figure 1: Soil treatment zone – Material dry density quadrant

If, for a given project, the nature of the material to be treated is known but not its dry density, refer to the indicative values of the table 1.

Materials	Dry density
Silt	**1,6 - 1,8**
Clay	**1,7 - 1,8**
Sand Homeometric sand Graduated sand	**1,4 - 1,9** 1,4 - 1,6 1,6 - 1,9
Granular soil	**1,8 - 2,2**

Table 1: dry density of different types of materials

1.3.2 - Quadrant 2

Once the binder quantity per m³ of soil has been determined by Quadrant 1, Quadrant 2 helps calculate its economic or environmental impact (Energy or CO_2).
In this Quadrant, we can see straight lines (going through the origin) which, depending on the graph used, will be either of economic or environmental nature (Energy or CO_2).
Each of these straight lines has an impact value that takes into account production and transport of binder between the plant and the construction site (figure 2).
So, for a given project, when the total impact (production + transport) per ton of binder is known, we simply prolong horizontally the straight line of Quadrant 1 to the intersection with the straight line corresponding to the chosen impact: the impact of the binder per m³ of treated soil can then be read directly on the other axis of Quadrant 2.

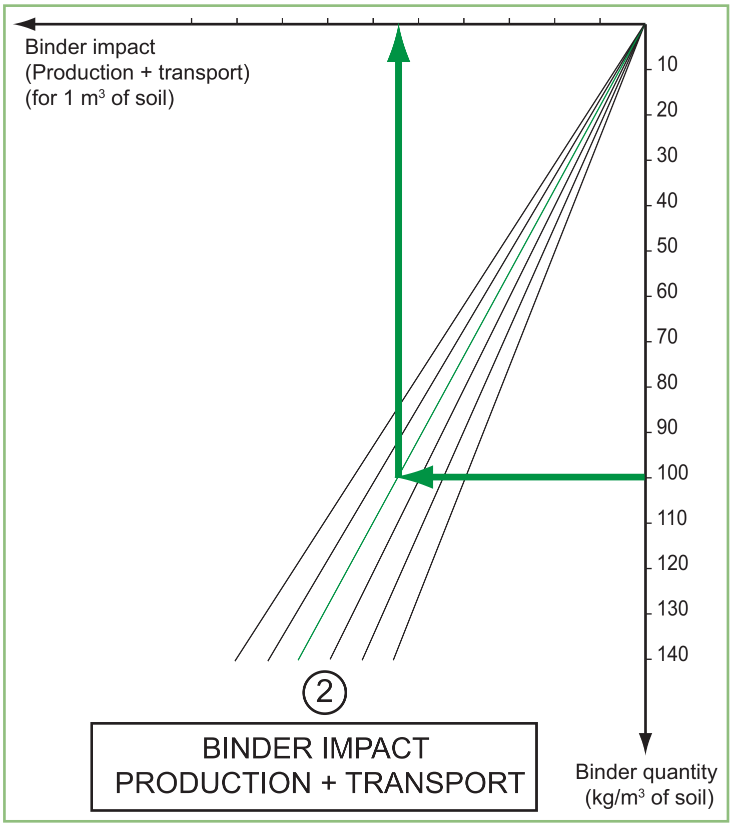


Figure 2: Soil treatment zone – Binder impact quadrant

If the impact per ton of binder is not known or if the user wishes to accurately determine this impact, considering the local data at hand, the user may refer to the diagram of figure 3.

When the transport distance between the cement plant and the construction site is known, as well as the transport impact in /t.km and the production impact per ton of binder, this diagram helps determine, successively, the transport impact and the total impact (production + transport). This last impact is then transferred on Quadrant 2, which will allow deducing the impact of the binder per m³ of treated soil.

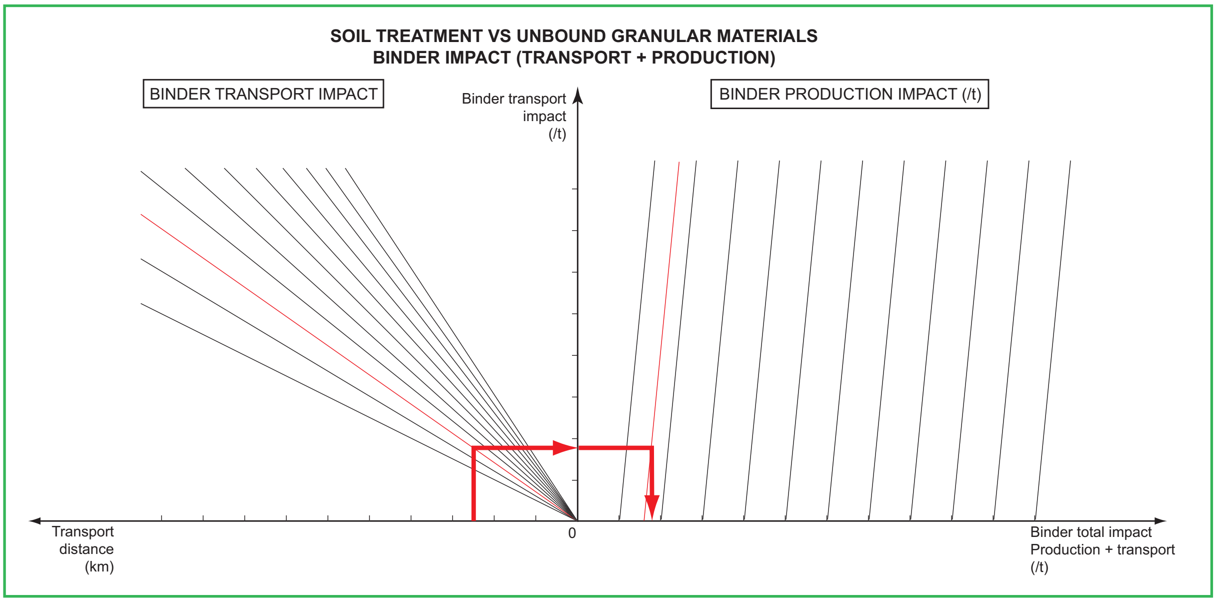


Figure 3: diagram of evaluation of binder impact (production + transport)

1.3.3 - Quadrant 3

It relates to the impact of placement.

In this Quadrant, we see parallel straight lines that correspond to different hypothesis relating to the impact of the placement equipment (spreader, mixer, sprinkler, compactor, grader).

These straight lines were drawn to include the combined impacts of Quadrants 2 and 3: they are thus tilted by an angle of 45° and have ordinates at the origin equivalent to the values of their impacts (figure 4).

As the impact value of the binder per m^3 of treated soil has been determined by Quadrant 2, we simply prolong vertically and upward the straight line obtained, to the intersection with the straight line that represents the impact of the placement equipment: the total combined impact per m^3 of treated soil can then be read directly on the other axis of Quadrant 3.

It is this value that will be considered to compare the impact of the Soil treatment technique and the impact of the unbound granular materials technique, for use in embankments.

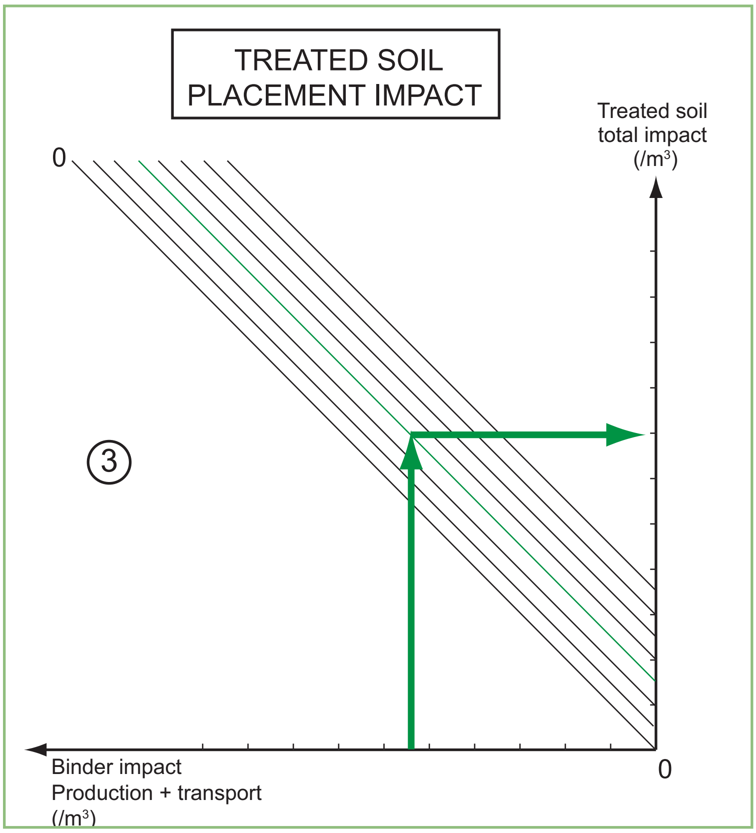


Figure 4: Soil treatment zone – Placement impact quadrant

1.3.4 - Quadrant 4

Using a simple geometrical construction (Thales' theorem), this quadrant enables to go from the impact per m³ of treated soil to the impact per m² of treated soil (figure 5).

It is this value that will be considered in order to compare the impact of the Soil treatment technique and the impact of the unbound granular materials technique, for use in capping layers.

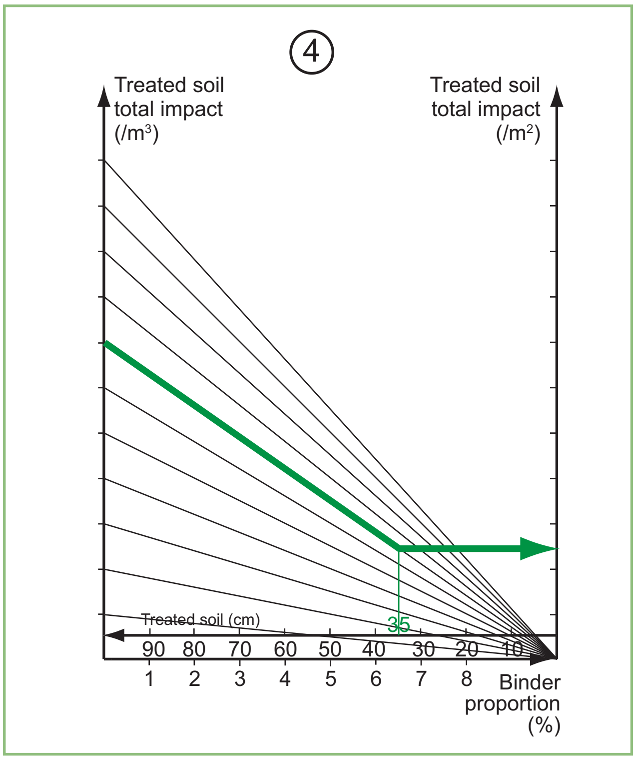


Figure 5: Soil treatment zone – Quadrant of total impact (/m³ et /m²)

1.4 - Study of Zone 2 – Unbound granular materials

This zone is divided into 4 quadrants numbered 5, 6, 7 and 8. Here are the main characteristics of each of these quadrants.

1.4.1 - Quadrant 5

It measures the impact of transport for the following materials:
- Unbound Granular materials, from the quarry to the construction site,
- Surplus soil (whose volume is supposed, in this document, equivalent to the volume of unbound granular material), from the construction site to the tip.

The straight lines of this Quadrant go through the origin and represent the economic or environmental impacts (Energy or CO_2) of the various transport modes used.

For a given project, knowing the distance between quarry and site as well as the distance between site and tip, we define an equivalent transport distance, i.e. the addition of quarry-site distance and site-tip distance. Once this equivalent distance is determined, and knowing the transport impact per m^3.km, we use this Quadrant to read off the transport impact per m^3 of materials, as indicated by the figure 6.

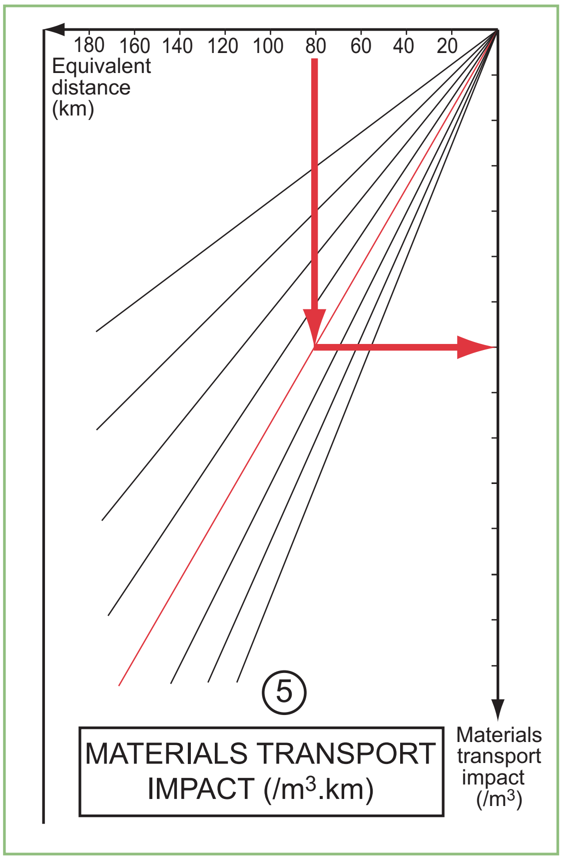


Figure 6: Unbound granular materials zone – Materials transport impact quadrant

1.4.2 - Quadrant 6

It measures the impact of extraction and production per m³ of aggregates.

In this Quadrant we see several parallel straight lines, corresponding to the impacts of various types of Unbound granular materials (rolled aggregate, crushed aggregate, hard rock, soft rock…).

These straight lines were drawn to include the combined impacts of Quadrants 5 and 6: they are thus tilted by an angle of 45° and have ordinates at the origin equivalent to the values of their impacts (figure 7).

As the value of the transport impact has been determined by Quadrant 5 and as the extraction and production impacts are known locally within the scope of this project, Quadrant 6 enables to assess:

- the tipping impact for a m³ of surplus soil,
- the extraction, production and transport impact for a m³ of aggregates.

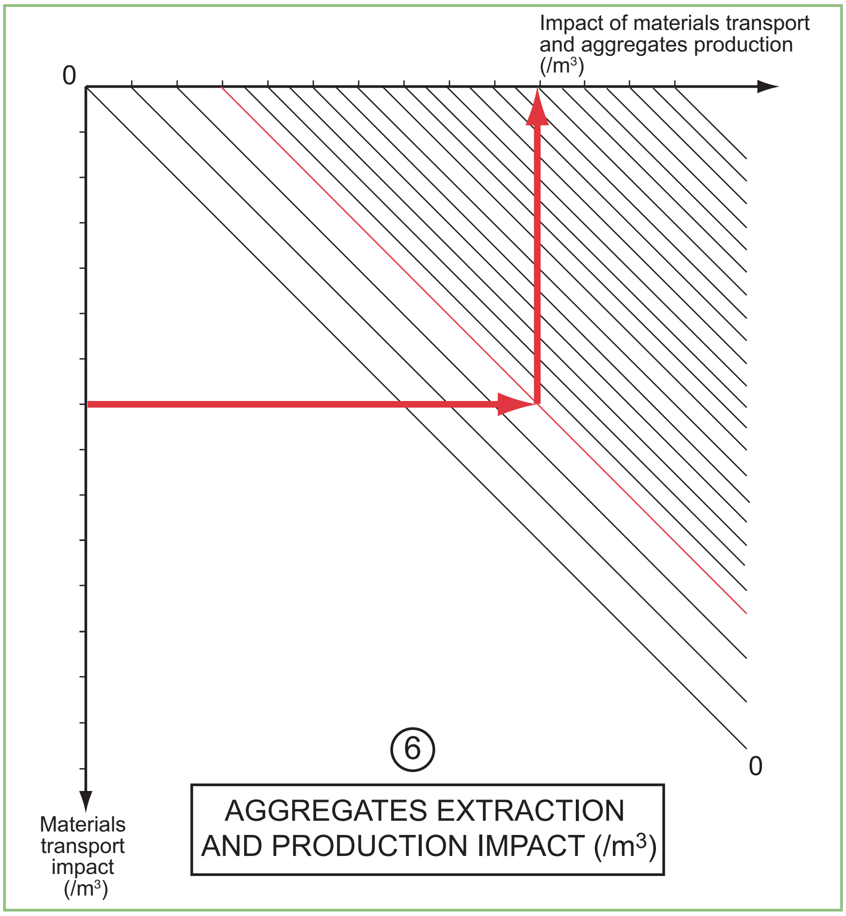


Figure 7: Unbound granular materials zone – Quadrant of aggregates extraction and production impact

1.4.3 - Quadrant 7

It measures the placement impact of Unbound granular materials.

In this Quadrant are parallel straight lines that correspond to different hypothesis relating to the impact of the placement equipment (grader, sprinkler, compactor).

These straight lines were drawn to include the combined impacts of Quadrants 5, 6 and 7: they are thus tilted by an angle of 45° and have ordinates at the origin equivalent to the values of their impacts (figure 8).

As the impacts of extraction, production and transport have been determined by Quadrant 6, and as the placement impact is known locally within the scope of this project, Quadrant 7 enables to evaluate the total combined impacts of tipping per m³ of surplus soil, and extraction, production, transport and placement impacts per m³ of aggregates.

It is this value that will be considered to compare the impact of the unbound granular materials technique and that of Soil treatment, for use in embankments.

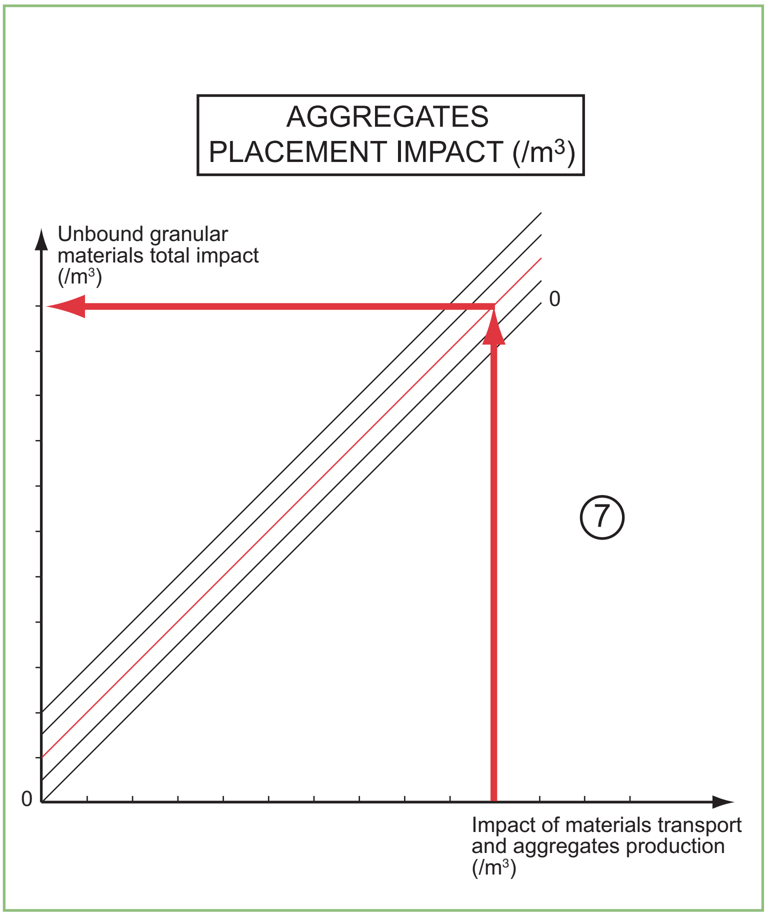


Figure 8: Unbound granular materials zone – Aggregates placement impact quadrant

1.4.4 - Quadrant 8

Using a simple geometrical construction (Thales' theorem), this quadrant enables to go from the impact per m^3 of granular base layer to the impact per m^2 of granular base layer (figure 9).

It is this value that will be considered in order to compare the impact of the unbound granular materials technique and that of Soil treatment, for use in capping layers.

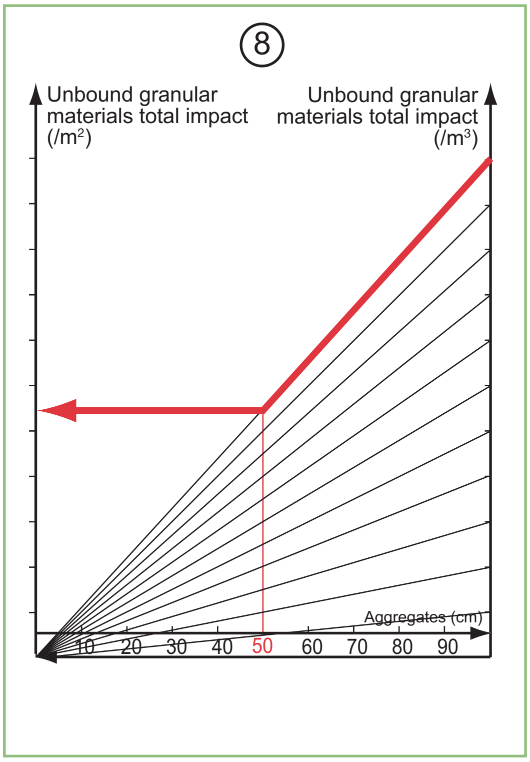


Figure 9: Unbound granular materials zone – Quadrant of total impact (/m³ et /m²)

1.5 - Conclusion

By applying this method on the 4 Quadrants of Zone 1 and on the 4 Quadrants of Zone 2 we can compare the impacts of the Soil treatment technique and the impacts of the Unbound granular materials technique.

For use in **embankments**, the comparison is made per m^3 of material (figure 10).

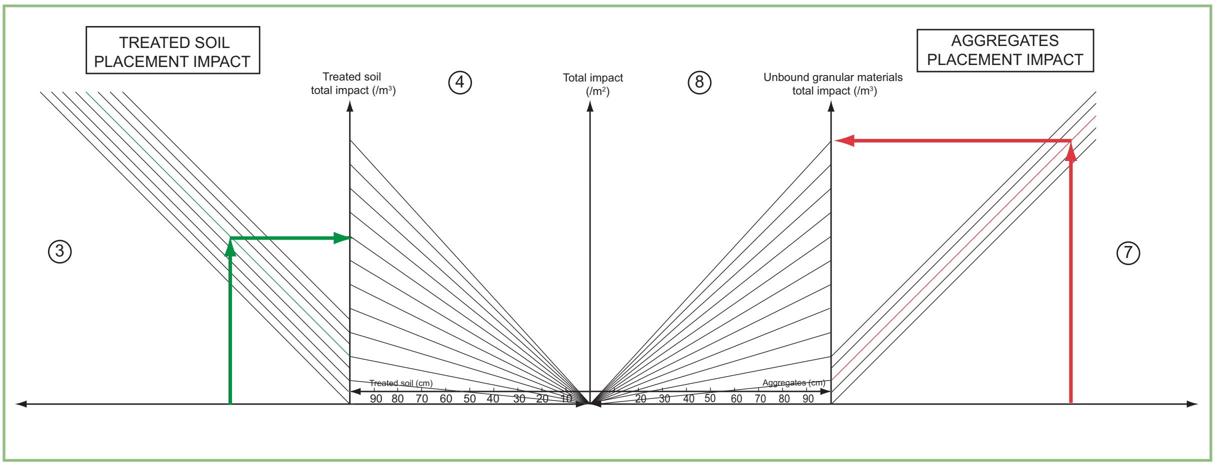


Figure 10: impacts comparison diagram – Embankments case

For use in **capping layers**, the comparison is made per m^2 of material (figure 11).

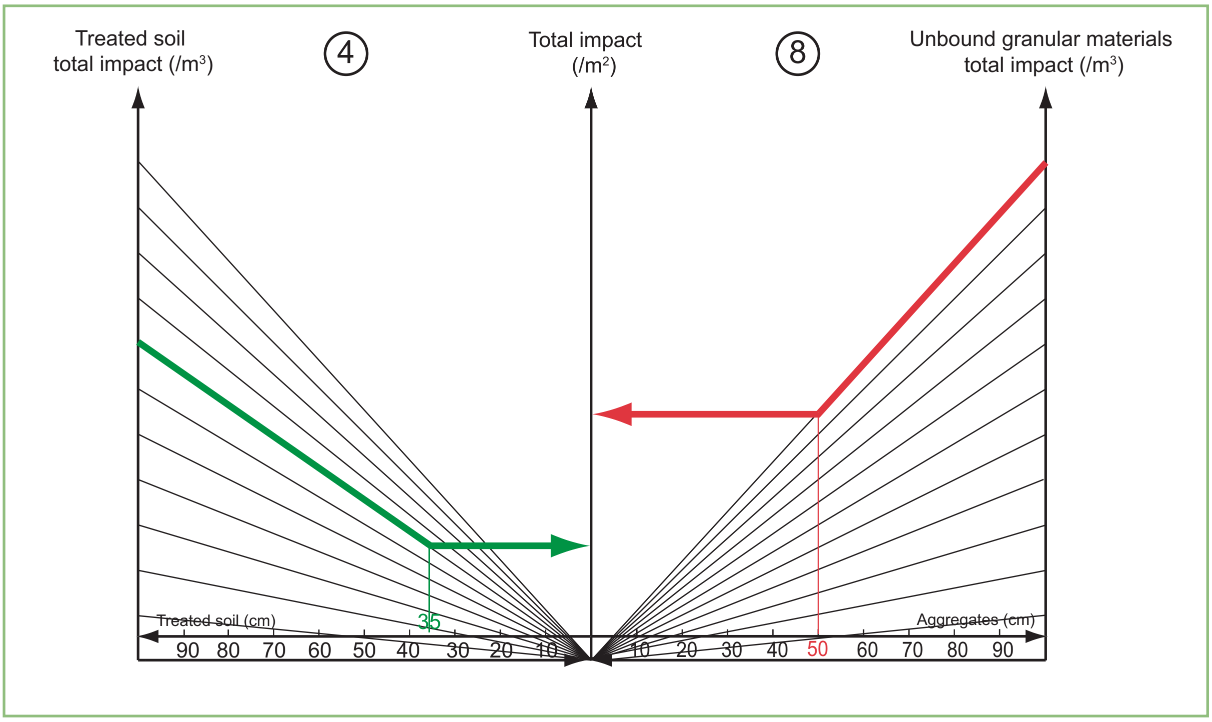


Figure 11: impacts comparison diagram – Capping layers case

Chapter 2

Economic comparison

2.1 - Study of Zone 1 – Soil treatment

This zone is divided into 4 quadrants numbered 1, 2, 3 and 4. Here are the main characteristics of each of these quadrants.

2.1.1 - Quadrant 1

It helps calculate the quantity of binder required per m³ of soil to reach the performances required for the material treated, within the scope of the project under study.

In this quadrant is a family of straight lines (going through the origin) that represent various dry densities, corresponding to a wide range of materials that can be found in nature (figure 12).

Thus, for a given project, when the dry density of the soil and the binder proportion are known, we simply draw a descending vertical line going from the binder proportion digit to the intersection with the straight line of the dry density chosen: the binder quantity per m³ of soil necessary for Soil treatment can then be read directly on the vertical axis of this Quadrant.

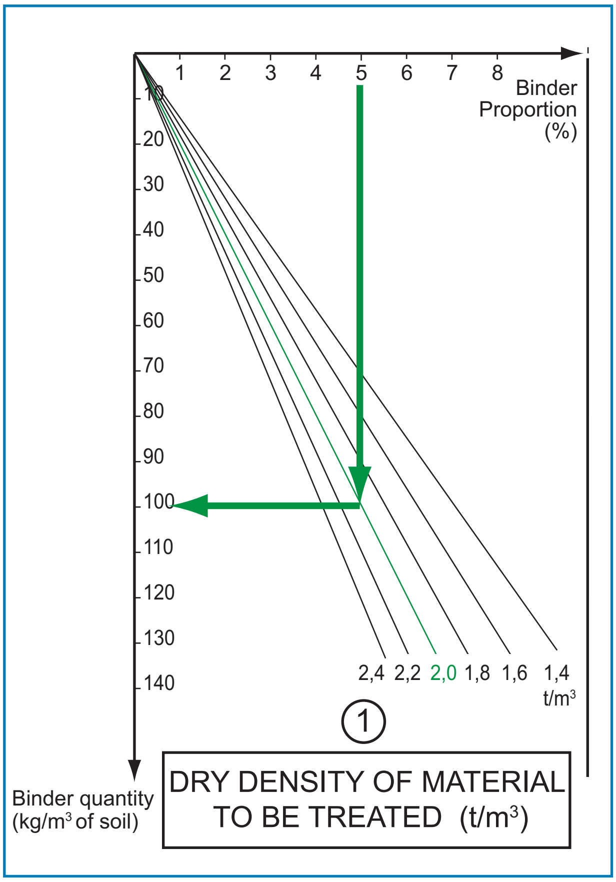


Figure 12: Soil treatment zone – Material dry density quadrant

If, for a given project, the nature of the material to be treated is known but not its dry density, refer to the indicative values of the table 2.

Materials	Dry density
Silt	**1,6 - 1,8**
Clay	**1,7 - 1,8**
Sand Homeometric sand Graduated sand	**1,4 - 1,9** 1,4 - 1,6 1,6 - 1,9
Granular soil	**1,8 - 2,2**

Table 2: dry density of different types of materials

■ *2.1.2 - Quadrant 2*

Once the binder quantity per m³ of soil has been determined by Quadrant 1, Quadrant 2 helps calculate its economic impact.
In this Quadrant, we can see straight lines (going through the origin) which represent the total cost (production and transport) for a ton of binder (figure 13).
So, for a given project, when the total cost (production + transport) per ton of binder is known, we simply prolong horizontally the straight line of Quadrant 1 to the intersection with the straight line of chosen cost: the binder cost per m³ of treated soil can then be read directly on the other axis of Quadrant 2.

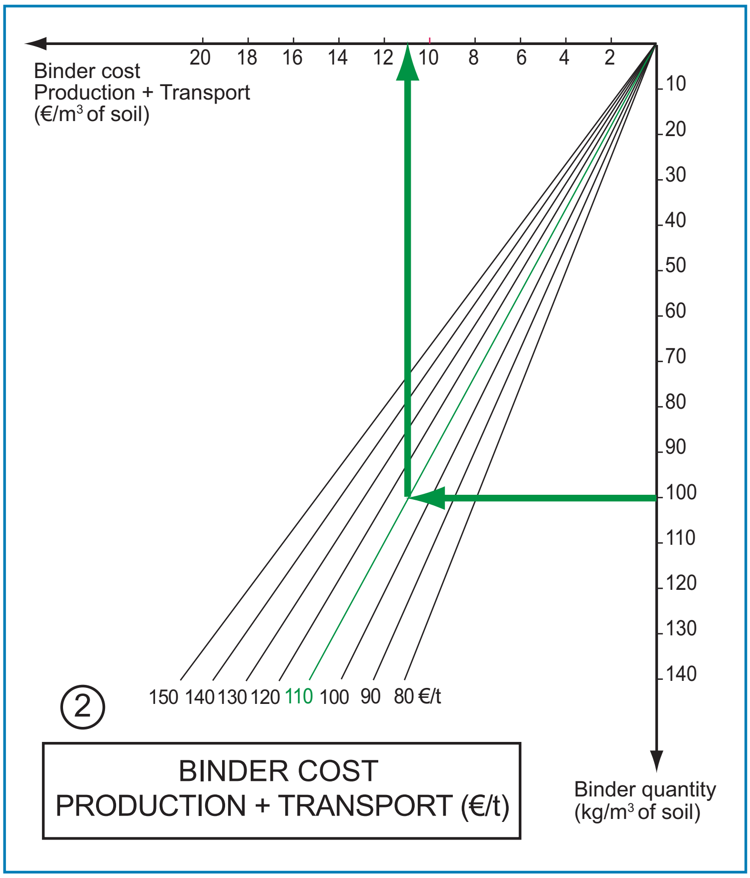


Figure 13: Soil treatment zone – Binder cost quadrant

2.1.3 - Quadrant 3

It relates to the impact of placement.

In this Quadrant, we see parallel straight lines that correspond to different hypothesis relating to the cost of the placement equipment (spreader, mixer, sprinkler, compactor, grader).

These straight lines were drawn to include the combined costs of Quadrants 2 and 3: they are thus tilted by an angle of 45° and have ordinates at the origin equivalent to their own values (figure 14).

As the cost of the binder per m³ of treated soil has been determined by Quadrant 2, we simply prolong vertically and upward the straight line obtained, to the intersection with the straight line that represents the cost of the placement equipment: the total combined cost per m³ of treated soil can then be read directly on the other axis of Quadrant 3.

It is this value that will be considered in order to compare the cost of the Soil treatment technique and the cost of the unbound granular materials technique, for use in embankments.

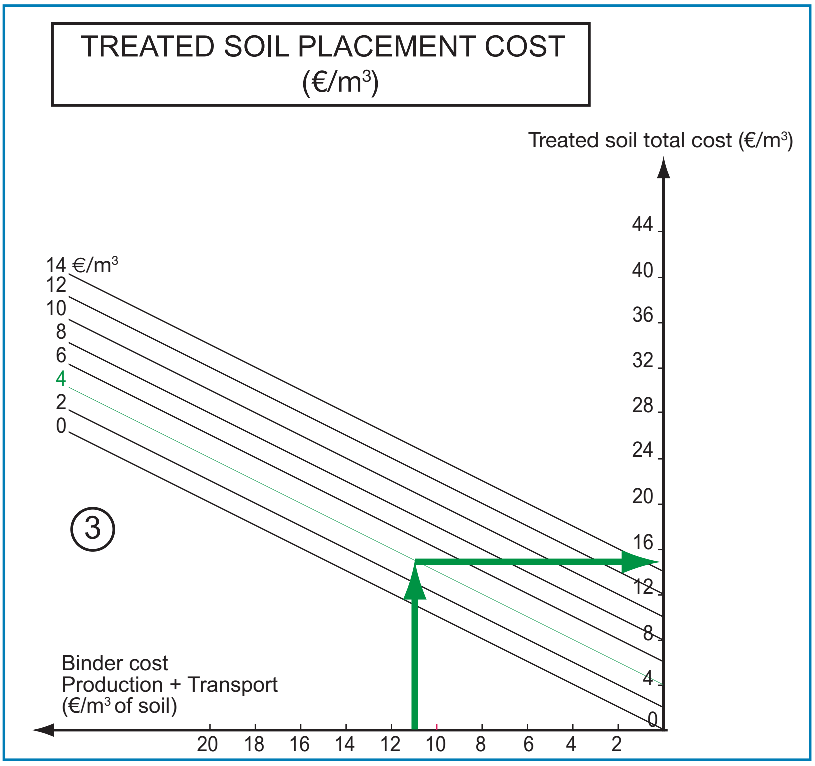


Figure 14: Soil treatment zone – Placement cost quadrant

2.1.4 - Quadrant 4

Using a simple geometrical construction (Thales' theorem), this quadrant enables to go from the cost per m³ of treated soil to the cost per m² of treated soil (figure 15).

It is this value that will be considered to compare the cost of the Soil treatment technique and the cost of the unbound granular materials technique, for use in capping layers.

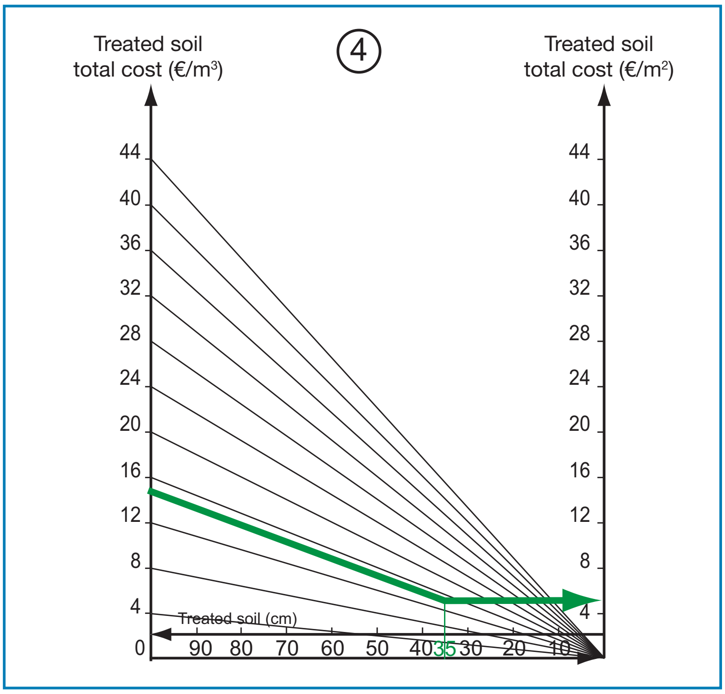


Figure 15: Soil treatment zone – Quadrant of total cost (/m³ et /m²)

2.2 - Study of Zone 2 – Unbound granular materials

This zone is divided into 4 quadrants numbered 5, 6, 7 and 8. Here are the main characteristics of each of these quadrants.

2.2.1 - Quadrant 5

It measures the cost of transport for the following materials:
- Unbound Granular materials, from the quarry to the construction site,
- Surplus soil (whose volume is supposed, in this document, equivalent to that of unbound granular materials), from the construction site to the tip.

The straight lines of this Quadrant go through the origin and represent the costs (expressed in €/m³.km) of the various transport modes used.

For a given project, knowing the distance between quarry and worksite as well as the distance between site and tip, we define an equivalent transport distance, i.e. the addition of quarry-site distance and site-tip distance. Once this equivalent distance is determined, and knowing the transport cost per m³.km, we use this Quadrant to read off the transport cost per m³ of materials, as indicated by the figure 16.

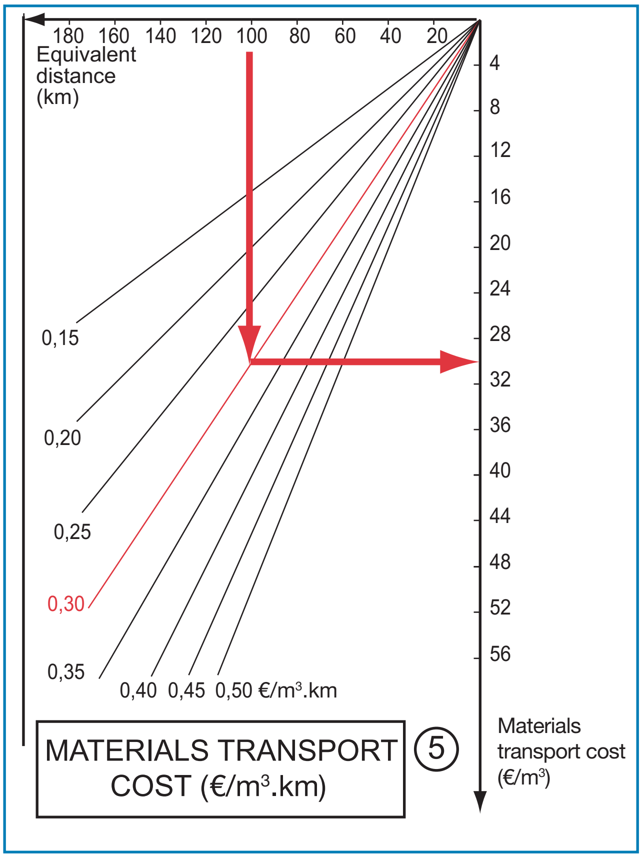


Figure 16: Unbound granular materials zone – Materials transport cost quadrant

2.2.2 - *Quadrant 6*

It measures the cost of extraction and production per m³ of aggregates.

In this Quadrant we see several parallel straight lines, corresponding to the costs of various types of Unbound granular materials (rolled aggregate, crushed aggregate, hard rock, soft rock...) expressed in €/m³ (figure 17).

These straight lines were drawn to include the combined costs of Quadrants 5 and 6: they are thus tilted by an angle of 45° and have ordinates at the origin equivalent to their own values.

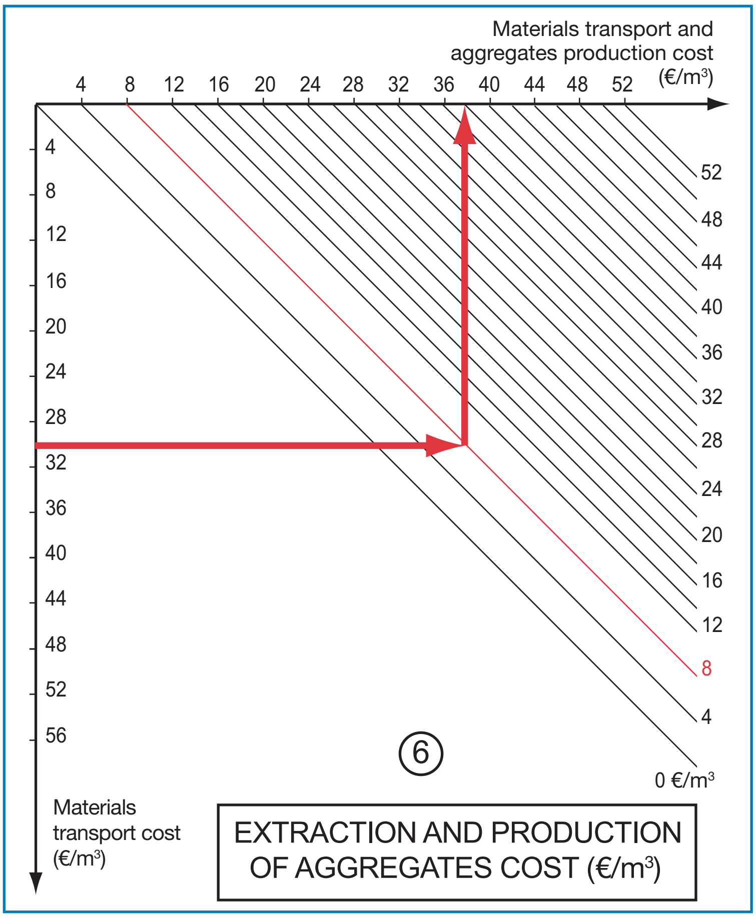


Figure 17: Unbound granular materials zone – Quadrant of aggregates extraction and production cost

As the transport cost has been determined at Quadrant 5 and as the extraction and production costs are known locally within the scope of this project, Quadrant 6 enables to calculate the cumulated total cost for tipping per m³ of surplus soil and total cost of extraction, production and transport per m³ of aggregates.

2.2.3 - Quadrant 7

It measures the placement cost of Unbound granular materials.

In this Quadrant are parallel straight lines that correspond to different hypothesis relating to the costs of placement equipment (grader, sprinkler, compactor).

These straight lines were drawn to include the combined costs of Quadrants 5, 6 and 7: they are thus tilted by an angle of 45° and have ordinates at the origin equivalent to their own values (figure 18).

As the cost of extraction, production and transport has been determined at Quadrant 6, and as the placement cost is known locally within the scope of this project, Quadrant 7 enables to evaluate the combined total cost for tipping per m³ of surplus soil and total cost of extraction, production, transport and placement per m³ of aggregates.

It is this value that will be considered in order to compare the cost of the unbound granular materials technique and that of Soil treatment, for use in embankments.

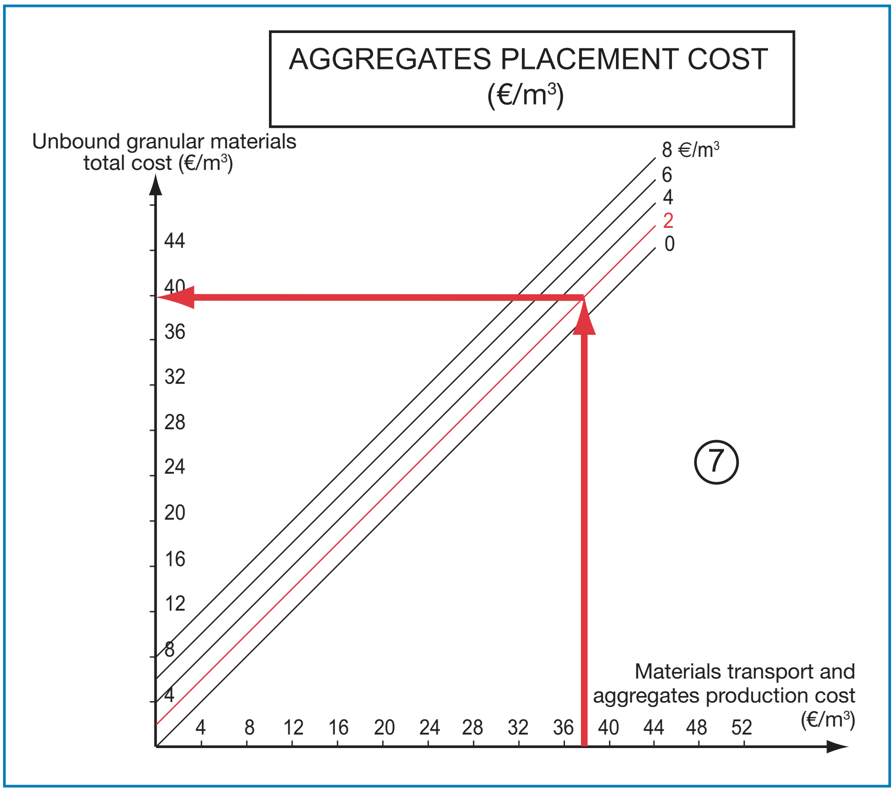


Figure 18: Unbound granular materials zone – Aggregates placement cost quadrant

■ 2.2.4 - *Quadrant 8*

Using a simple geometrical construction (Thales' theorem), this quadrant enables to go from the cost per m³ of granular base layer to the cost per m² of granular base layer.

It is this value that will be considered in order to compare the cost of the unbound granular materials technique and that of Soil treatment, for use in capping layers (figure 19).

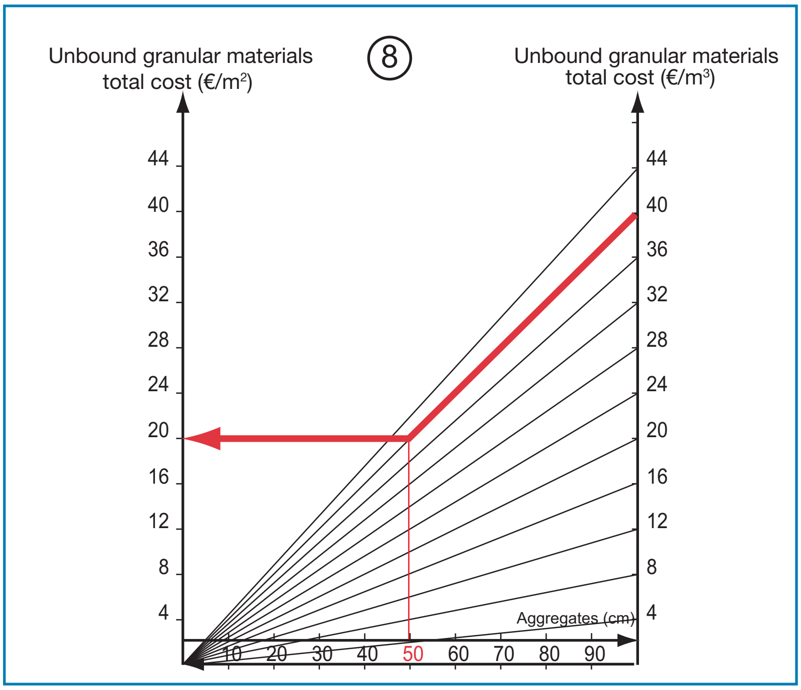


Figure 19: Unbound granular materials zone – Quadrant of total cost (/m³ et /m²)

2.3 - Conclusion

By applying this method on the 4 Quadrants of Zone 1 and on the 4 Quadrants of Zone 2 we can compare the costs of the Soil treatment technique and the costs of the unbound granular materials technique.

For use in **embankments**, the comparison is made per m³ of material (figure 20).

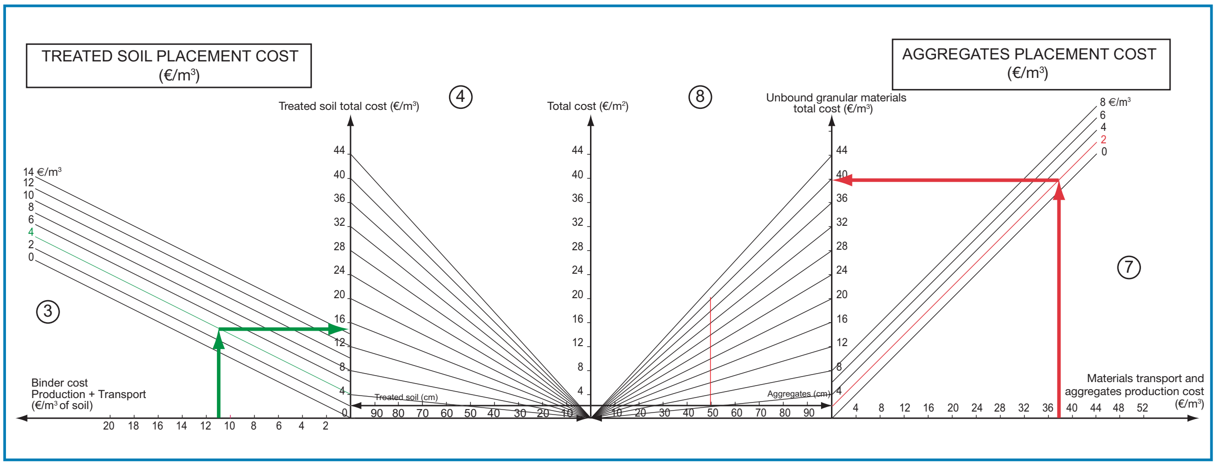


Figure 20: costs comparison diagram – Embankments case

For use in **capping layers** the comparison is made per m² of material (figure 21).

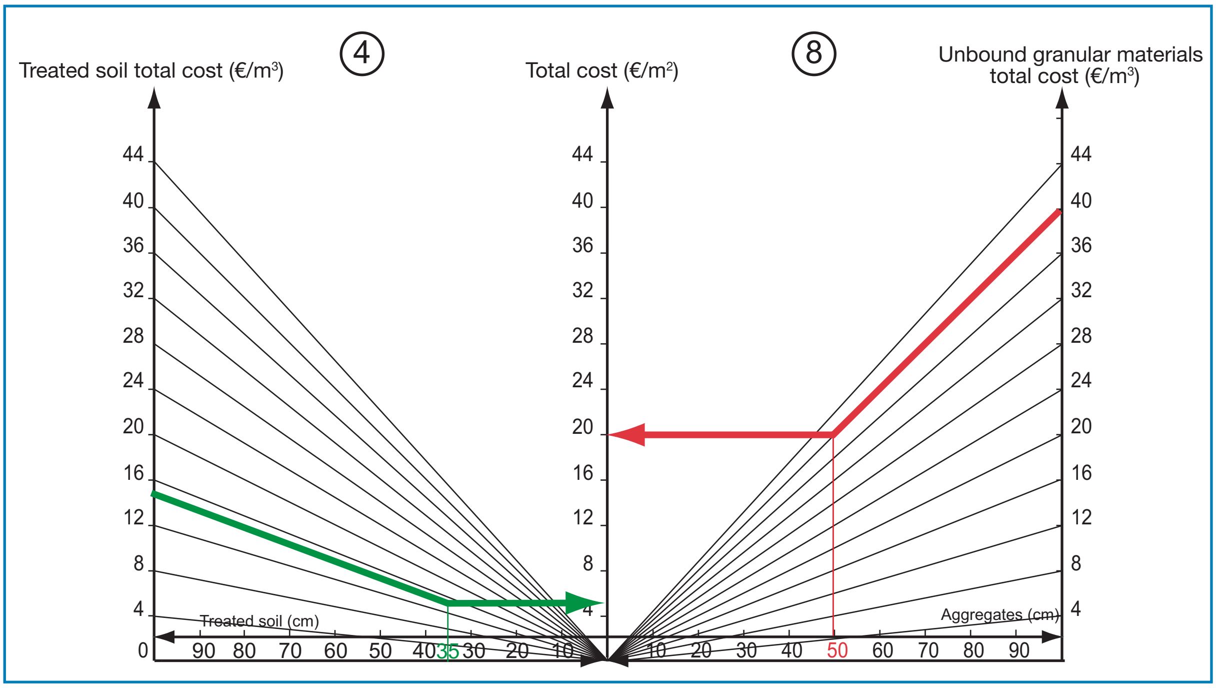
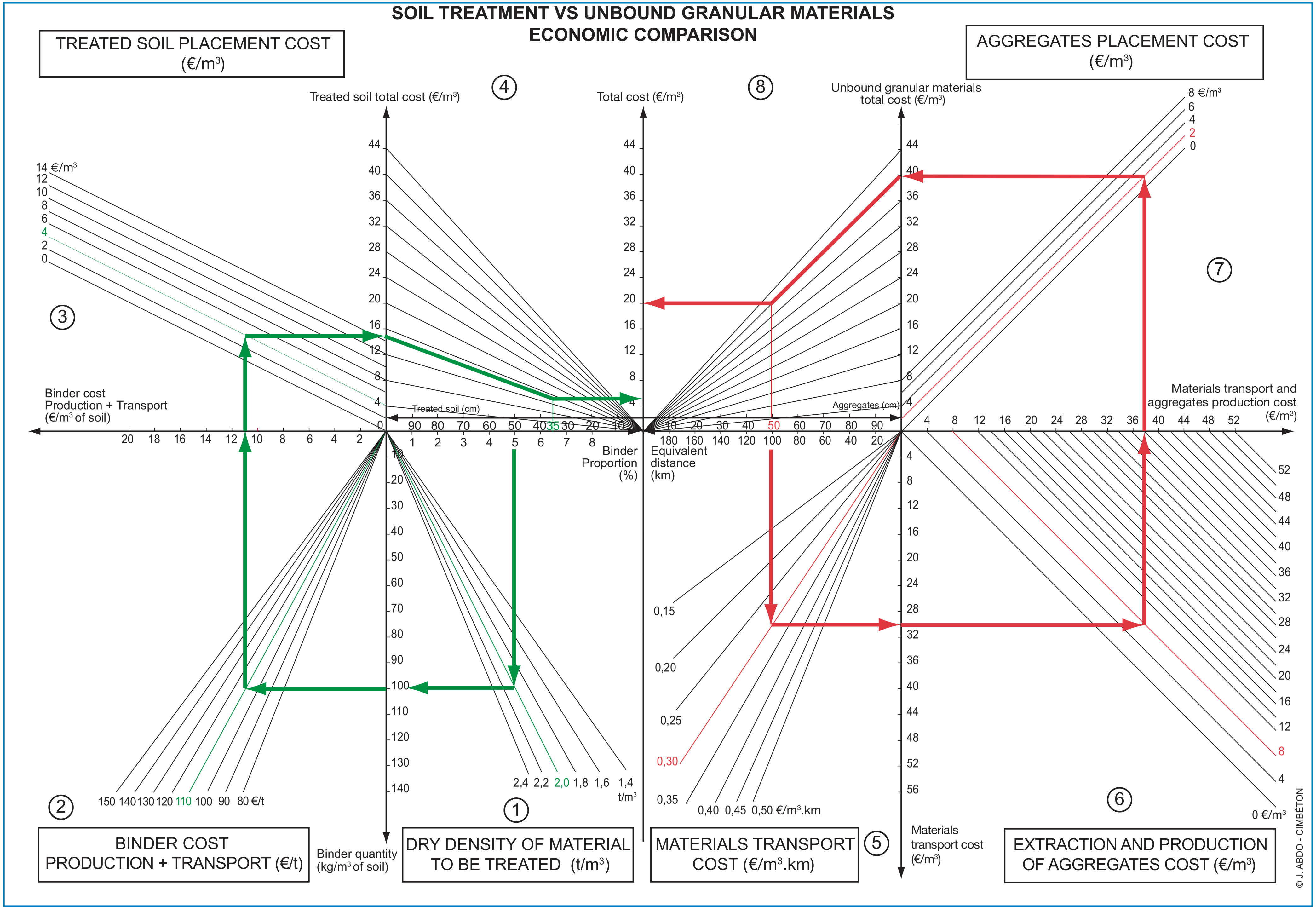


Figure 21: costs comparison diagram – Capping layers case



SOIL TREATMENT VS UNBOUND GRANULAR MATERIALS
ECONOMIC COMPARISON
TREATED SOIL PLACEMENT COST (€/m³)
AGGREGATES PLACEMENT COST (€/m³)
Treated soil total cost (€/m³)
Total cost (€/m²)
Unbound granular materials total cost (€/m³)
Binder cost Production + Transport (€/m³ of soil)
Materials transport and aggregates production cost (€/m³)
Treated soil (cm)
Aggregates (cm)
Binder Proportion (%)
Equivalent distance (km)
Binder quantity (kg/m³ of soil)
Materials transport cost (€/m³)
BINDER COST PRODUCTION + TRANSPORT (€/t)
DRY DENSITY OF MATERIAL TO BE TREATED (t/m³)
MATERIALS TRANSPORT COST (€/m³.km)
EXTRACTION AND PRODUCTION OF AGGREGATES COST (€/m³)
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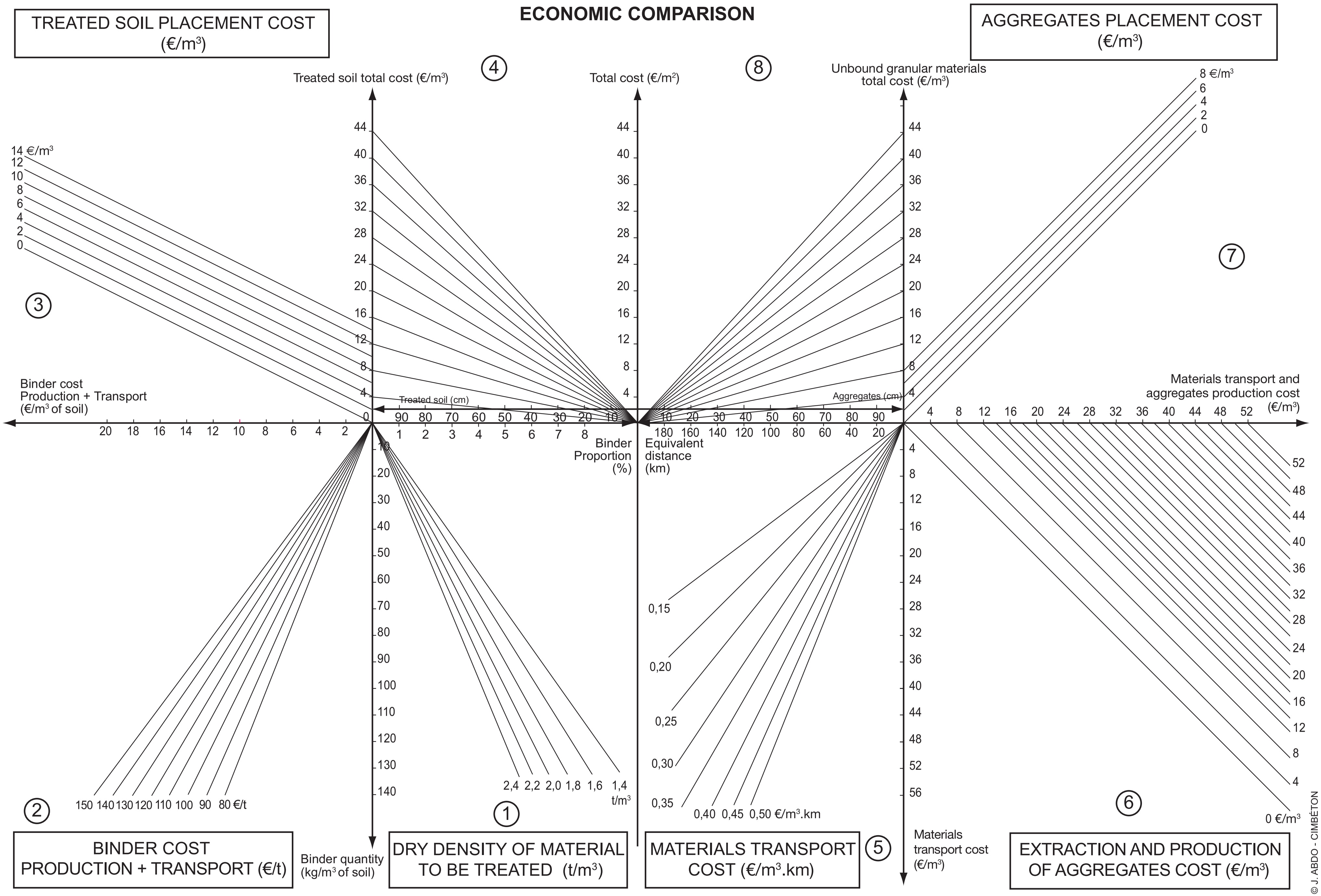
To make your own economic comparison studies between the Soil treatment technique and the Unbound granular materials technique, you can simply photocopy the unmarked graph on page 35, add data specific to your study and read the result you need on the graph.

SOIL TREATMENT VS UNBOUND GRANULAR MATERIALS ECONOMIC COMPARISON



Chapter 3

Environmental comparison – Energy Indicator

3.1 - Study of Zone 1 – Soil treatment

This zone is divided into 4 quadrants numbered 1, 2, 3 and 4. Here are the main characteristics of each of these quadrants.

3.1.1 - Quadrant 1

It helps calculate the quantity of binder required per m³ of soil to reach the performances required for the material treated, within the scope of the project under study.

In this quadrant is a family of straight lines (going through the origin) that represent various dry densities, corresponding to a wide range of materials that can be found in nature (figure 22).

Thus, for a given project, when the dry density of the soil and the binder proportion are known, we simply draw a descending vertical line going from the binder proportion digit to the intersection with the straight line of the dry density chosen: the binder quantity per m³ of soil necessary for Soil treatment can then be read directly on the vertical axis of this Quadrant.

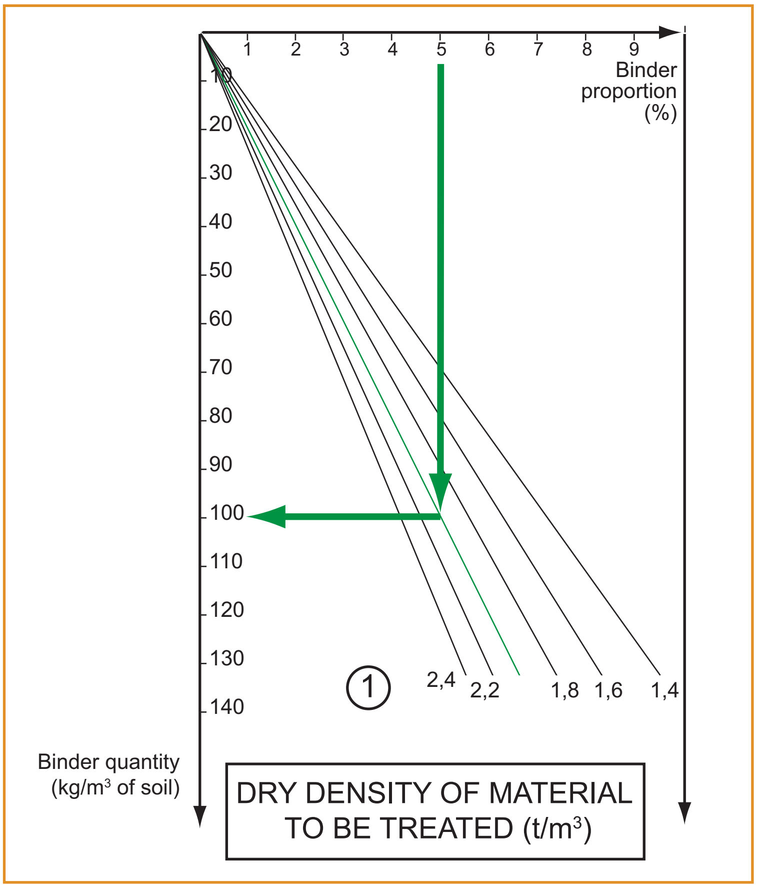


Figure 22: Soil treatment zone – Material dry density quadrant

If, for a given project, the nature of the material to be treated is known but not its dry density, refer to the indicative values of the table 3.

Materials	Dry density
Silt	**1,6 - 1,8**
Clay	**1,7 - 1,8**
Sand Homeometric sand Graduated sand	**1,4 - 1,9** 1,4 - 1,6 1,6 - 1,9
Granular soil	**1,8 - 2,2**

Table 3: dry density of different types of materials

3.1.2 - Quadrant 2

Once the binder quantity per m³ of soil has been determined by Quadrant 1, Quadrant 2 helps calculate its Energy impact.
In this Quadrant, we can see straight lines (going through the origin) which represent the Energy impact (production + transport) for a ton of binder (figure 23).
So, for a given project, when the total Energy (production + transport) per ton of binder is known, we simply prolong horizontally the straight line of Quadrant 1 to the intersection with the straight line corresponding to the chosen Energy: the Energy of the binder per m³ of treated soil can then be read directly on the other axis of Quadrant 2.

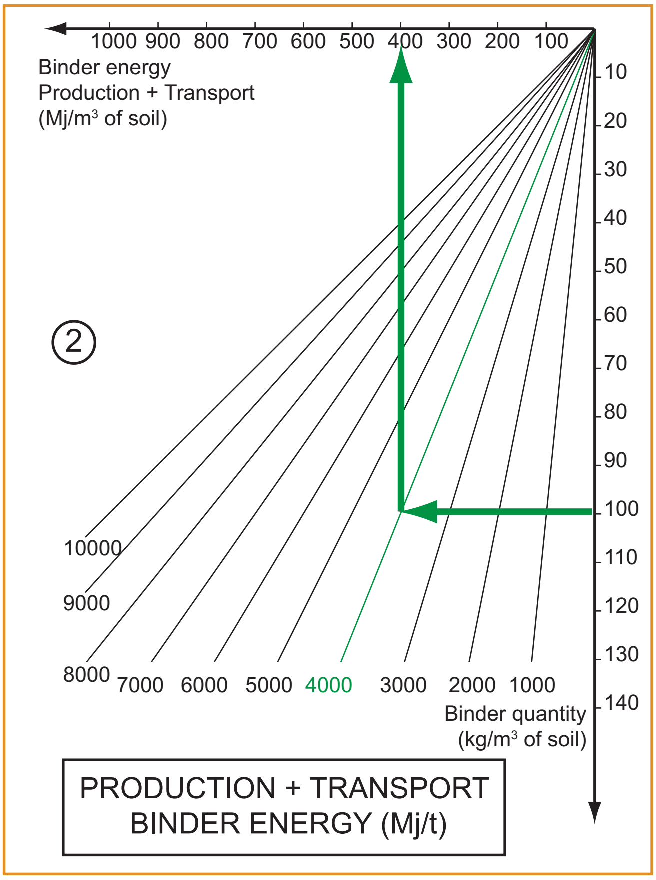


Figure 23: Soil treatment zone – Binder Energy quadrant

If the total energy per ton of binder is not known or if the user wishes to accurately determine this energy with the local data at hand, he may refer to the diagram of figure 24.

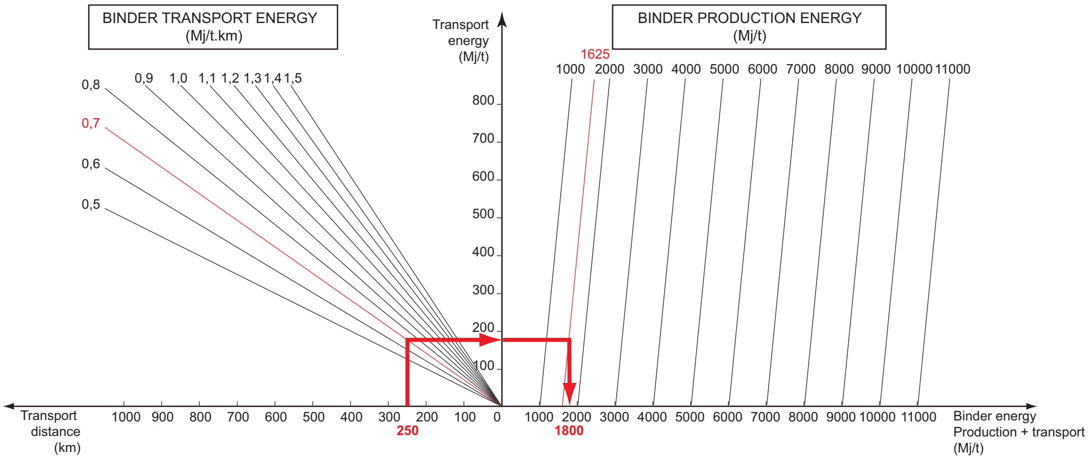


Figure 24: diagram of evaluation of binder Energy (production + transport)

When the transport distance between the cement plant and the construction site is known, as well as the transport energy of binder in Mj/t.km and the production energy for a ton of binder, this diagram helps determine, successively, the transport energy and the total energy.
The total energy is then transferred on Quadrant 2, which will allow deducing the energy of the binder per m³ of treated soil.

3.1.2.1 - Transport Energy

When the binder transport energy in Mj/t.km is not known, the user is able to calculate it using the following formula: moyen de la formule suivante :

$$\textbf{F (Energy, D)} = \frac{\textbf{Consumption per 100 km x 35}}{\textbf{Truck load capacity x 100}}$$

With:

Consumption per 100 km
16-ton truck: 29 litres of fuel
29-ton truck: 36 litres of fuel
40-ton truck: 40 litres of fuel

Truck load capacity
16-ton truck: 8-ton load capacity
29-ton truck: 16-ton load capacity
40-ton truck: 20-ton load capacity

Coefficient 35: this is the quantity of energy (in Mj) released by the combustion of a litre of fuel

Coefficient 100: for 100 km

3.1.2.2 - Binder production Energy

When the production energy per ton of binder is not known, we can use the values given as an indication in the table 4.

Binder	Energy consumption (Mj/t binder)
CEM I	5 930*
CEM II	4 395*
Hydraulic Road Binder HRB 70% Slag	2 636*
Hydraulic Road Binder HRB 50% Slag	3 459*
Hydraulic Road Binder HRB 30% Slag	4 282*
Hydraulic Road Binder HRB 30% Limestone	3 856*
Hydraulic Road Binder HRB 30% Fly Ash	3 887*
Quicklime	4 301**

** Source: ATILH* *** Source: Union des Producteurs de Chaux*

Table 4: Binder production Energy

To obtain the right production energy per ton of a given product, we invite you to contact directly the binder's producer.

3.1.3 - Quadrant 3

It relates to the Energy consumed during placement.

In this Quadrant we see parallel straight lines that correspond to different hypothesis relating to the energies consumed by the placement equipment (spreader, mixer, sprinkler, compactor, grader).

These straight lines were drawn to include the combined energies of Quadrants 2 and 3: they are thus tilted by an angle of 45° and have ordinates at the origin equivalent to their own values (figure 25).

As the energy value of the binder per m^3 of treated soil has been determined by Quadrant 2, we simply prolong vertically and upward the straight line obtained, to the intersection with the straight line that represents the energy of the placement equipment: the total combined energy per m^3 of treated soil can then be read directly on the other axis of Quadrant 3.

It is this value that will be considered in order to compare the total Energy of the Soil treatment technique and the total Energy of the unbound granular materials technique, for use in embankments.

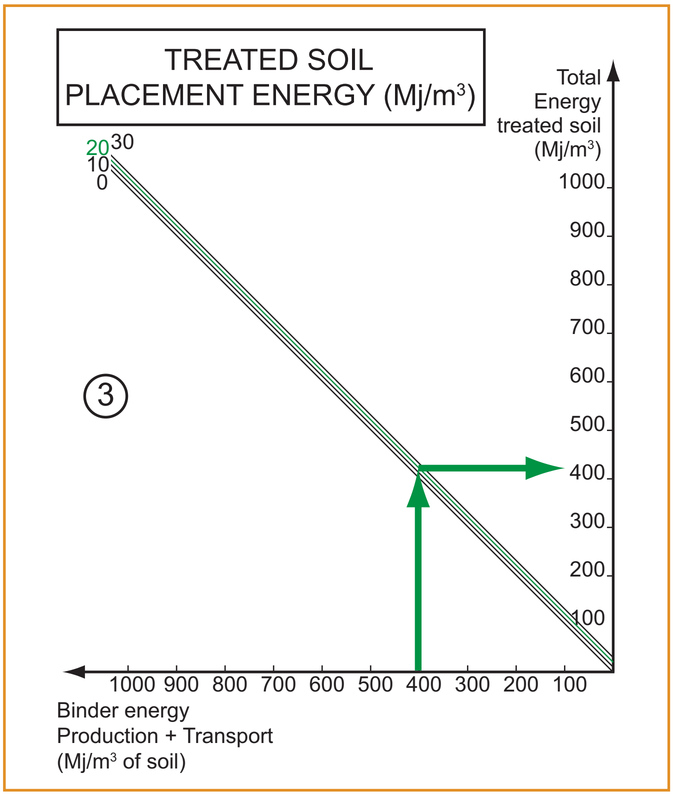


Figure 25: Soil treatment zone – Placement Energy quadrant

If the energy of the placement equipment is not known, we can use the following calculation method:

$$E_{Mj} = 35\ L_{Litre}$$

With:

E: energy consumed for the placement of a m³ of treated soil (Mj)

Coefficient 35: calorific value of a litre of fuel

L fuel consumption of all equipment used for placement of treated soil (for 1 m³). **L** values are given in the table 5.

L	Soil
0,7	Silty/sandy soil
0,8	Clay soil
0,9	Gravelly soil
1,0	Packed and difficult soil
> 1,0	Bouldery soil

Table 5: fuel consumption of all equipment used for placement treated Soil, according to soil nature

3.1.4 - Quadrant 4

Using a simple geometrical construction (Thales' theorem), this quadrant enables to go from the Energy per m^3 of treated soil to the Energy per m^2 of treated soil (figure 26).

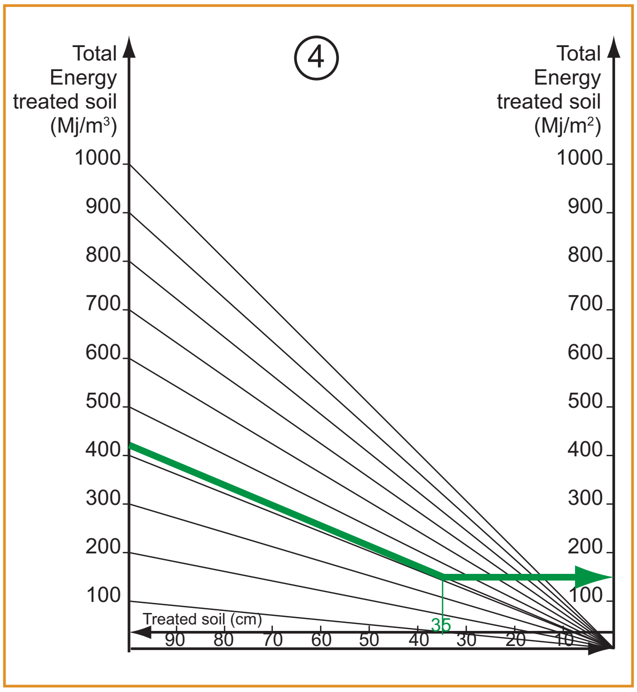


Figure 26: Soil treatment zone – Quadrant of total Energy (/m^3 et /m^2)

It is this value that will be considered to compare the total Energy of the Soil treatment technique and the Energy of the unbound granular materials technique, for use in capping layers.

3.2 - Study of Zone 2 – Unbound granular material

This zone is divided into 4 quadrants numbered 5, 6, 7 and 8. Here are the main characteristics of each of these quadrants.

3.2.1 - Quadrant 5

IIt measures the Energy of the following materials:
- Unbound Granular materials, from the quarry to the construction site,
- Surplus soil (whose volume is supposed, in this document, equivalent to that of unbound granular materials), from the construction site to the tip.

The straight lines of this Quadrant go through the origin and represent the energies (expressed in Mj/m³.km) of the various transport modes used (figure 27).

For a given project, knowing the distance between quarry and worksite as well as the distance between site and tip, we define an equivalent transport distance, i.e. the addition of quarry-site distance and site-tip distance. Once this equivalent distance is determined, and knowing the transport energy per m³.km, we use this Quadrant to read off the transport energy per m³ of materials, as indicated by the red line on the graph below.

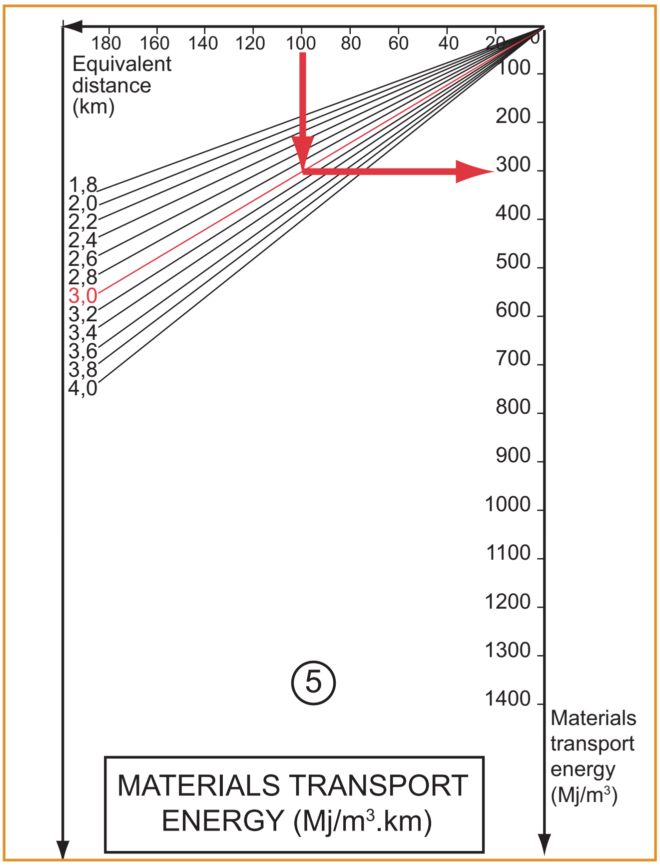


Figure 27: Unbound granular materials zone – Materials transport Energy quadrant

When the transport energy per m^3.km is not known, the user is able to calculate it using the following formula:

$$F\ (\text{Energy, D}) = \frac{\text{Consumption per 100 km} \times 35 \times 2.2}{\text{Truck load capacity} \times 100}$$

With:

Consumption per 100 km
16-ton truck: 29 litres of fuel
29-ton truck: 36 litres of fuel
40-ton truck: 40 litres of fuel

Truck load capacity
16-ton truck: 8-ton load capacity
29-ton truck: 16-ton load capacity
40-ton truck: 20-ton load capacity

Coefficient 35: this is the quantity of energy (in megajoules - Mj) released by the combustion of a litre of fuel

Coefficient 100: for 100 km

Coefficient 2.2: density of aggregates

■ *3.2.2 - Quadrant 6*

It measures the Energy of extraction and production per m^3 of aggregates.

In this Quadrant we see several parallel straight lines, corresponding to the energies of various types of Unbound granular materials (rolled aggregate, crushed aggregate, hard rock, soft rock…).

These straight lines were drawn to include the combined energies of Quadrants 5 and 6: they are thus tilted by an angle of 45° and have ordinates at the origin equivalent to their own values (figure 28).

As the transport energy has been determined at Quadrant 5 and as the extraction and production energies are known locally within the scope of this project, Quadrant 6 enables to calculate the combined energy of materials transport, of extraction and production of aggregates.

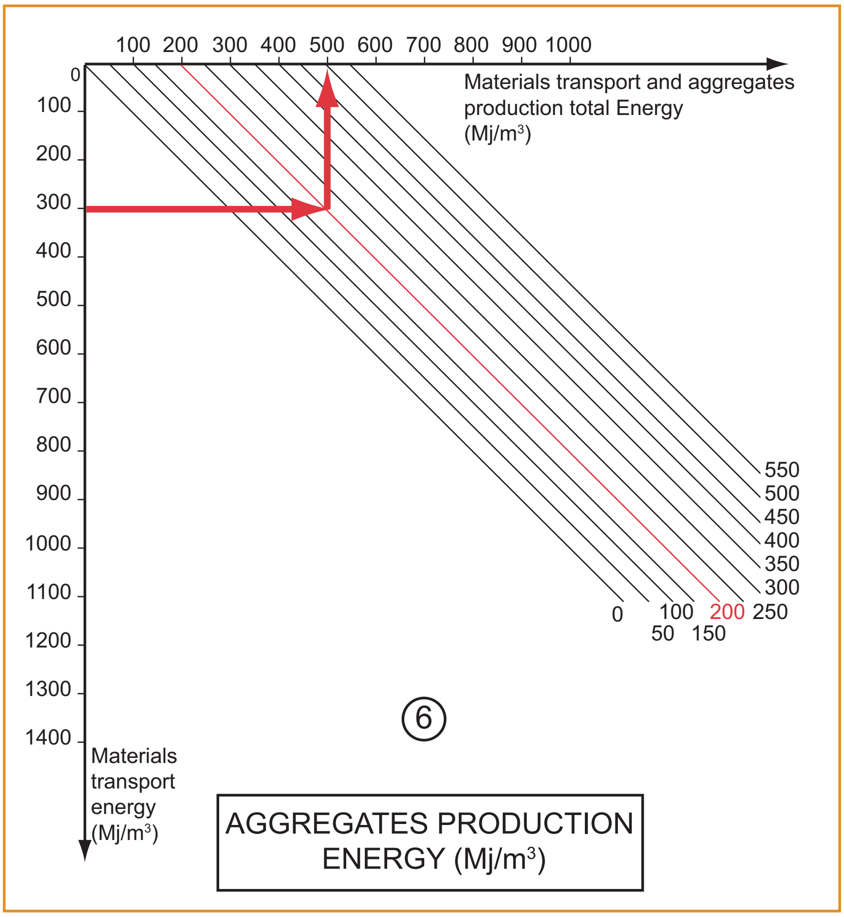


Figure 28: Unbound granular materials zone – Quadrant of aggregates extraction and production Energy

3.2.3 - Quadrant 7

It measures the placement energy of Unbound granular materials.

In this Quadrant are parallel straight lines that correspond to different hypothesis relating to the energies of placement equipment (grader, sprinkler, compactor).

These straight lines were drawn to include the combined energies of Quadrants 5, 6 and 7: they are thus tilted by an angle of 45° and have ordinates at the origin equivalent to their own values (figure 29).

As the energy of extraction, production and transport has been determined at Quadrant 6, and as the placement energy is known locally within the scope of this project, Quadrant 7 enables to evaluate the combined total energy of materials transport, of extraction, production and placement of aggregates.

It is this value that will be considered in order to compare the total energy of the unbound granular materials technique and that of the Soil treatment technique, for use in embankments.

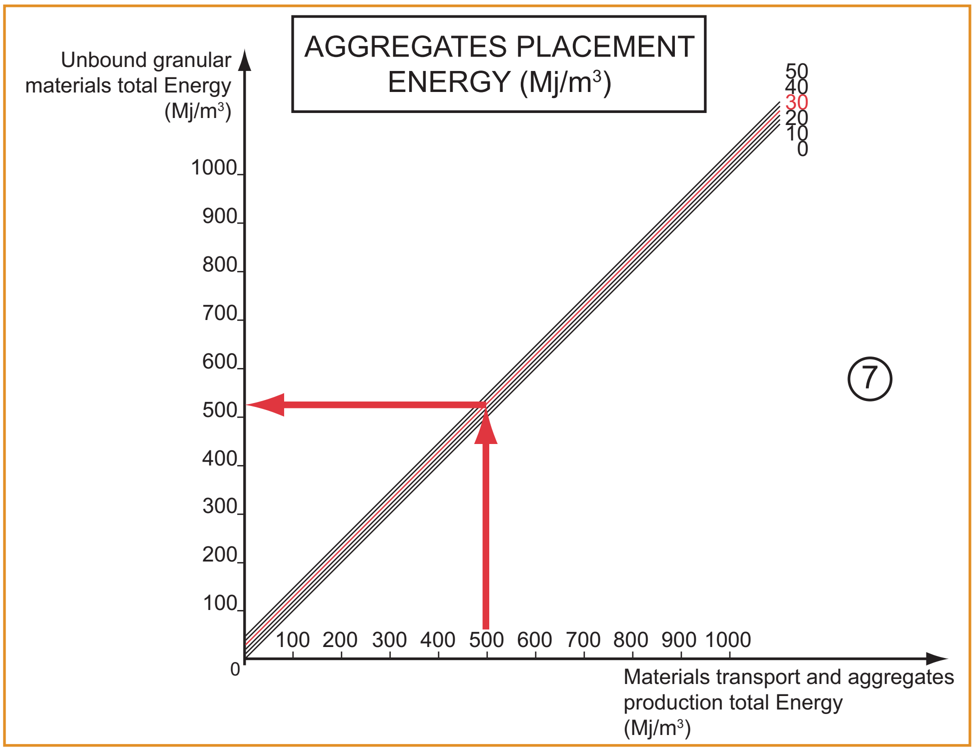


Figure 29: Unbound granular materials zone – Aggregates placement Energy quadrant

3.2.4 - Quadrant 8

Using a simple geometrical construction (Thales' theorem), this quadrant enables to go from the Energy per m³ of treated soil to the Energy per m² of treated soil (figure 30). It is this value that will be considered to compare the total Energy of the Soil treatment technique and the Energy of the unbound granular materials technique, for use in capping layers.

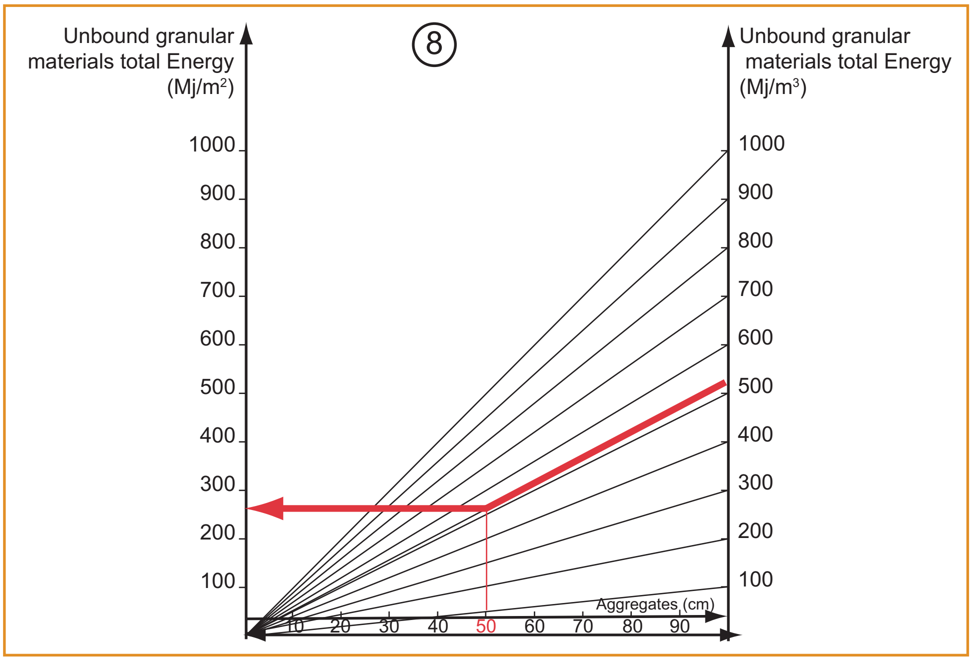


Figure 30: Unbound granular materials zone – Quadrant of total Energy (/m³ et /m²)

3.3 - Conclusion

By applying this method on the 4 Quadrants of Zone 1 and on the 4 Quadrants of Zone 2 we can compare the energie of the Soil treatment technique and the energie of the unbound granular materials technique.

For use in **embankments**, the comparison is made per m³ of material (figure 31).

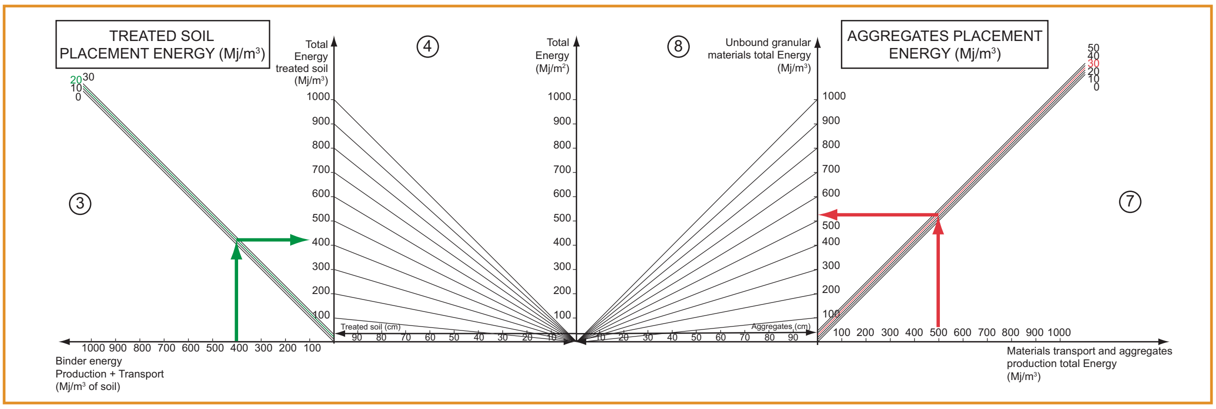


Figure 31: environmental comparison diagram (Energy) – Embankments case

For use in **capping layers**, the comparison is made per m² of material (figure 32).

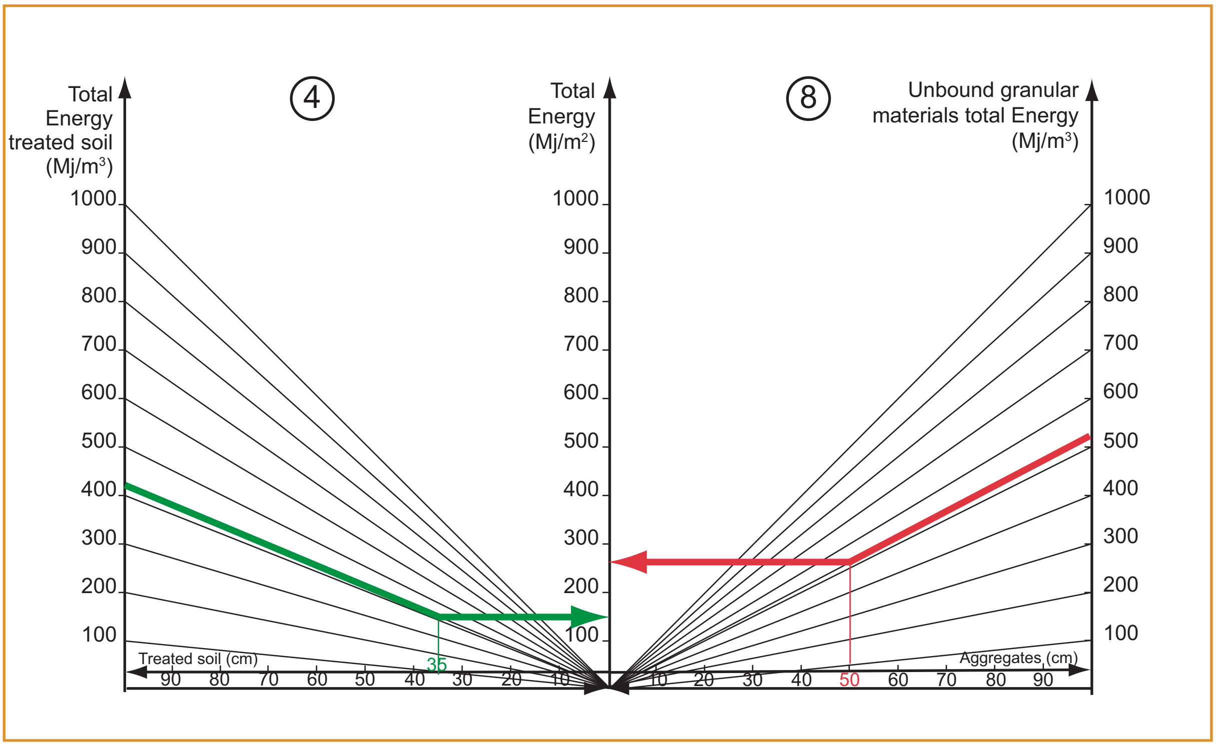
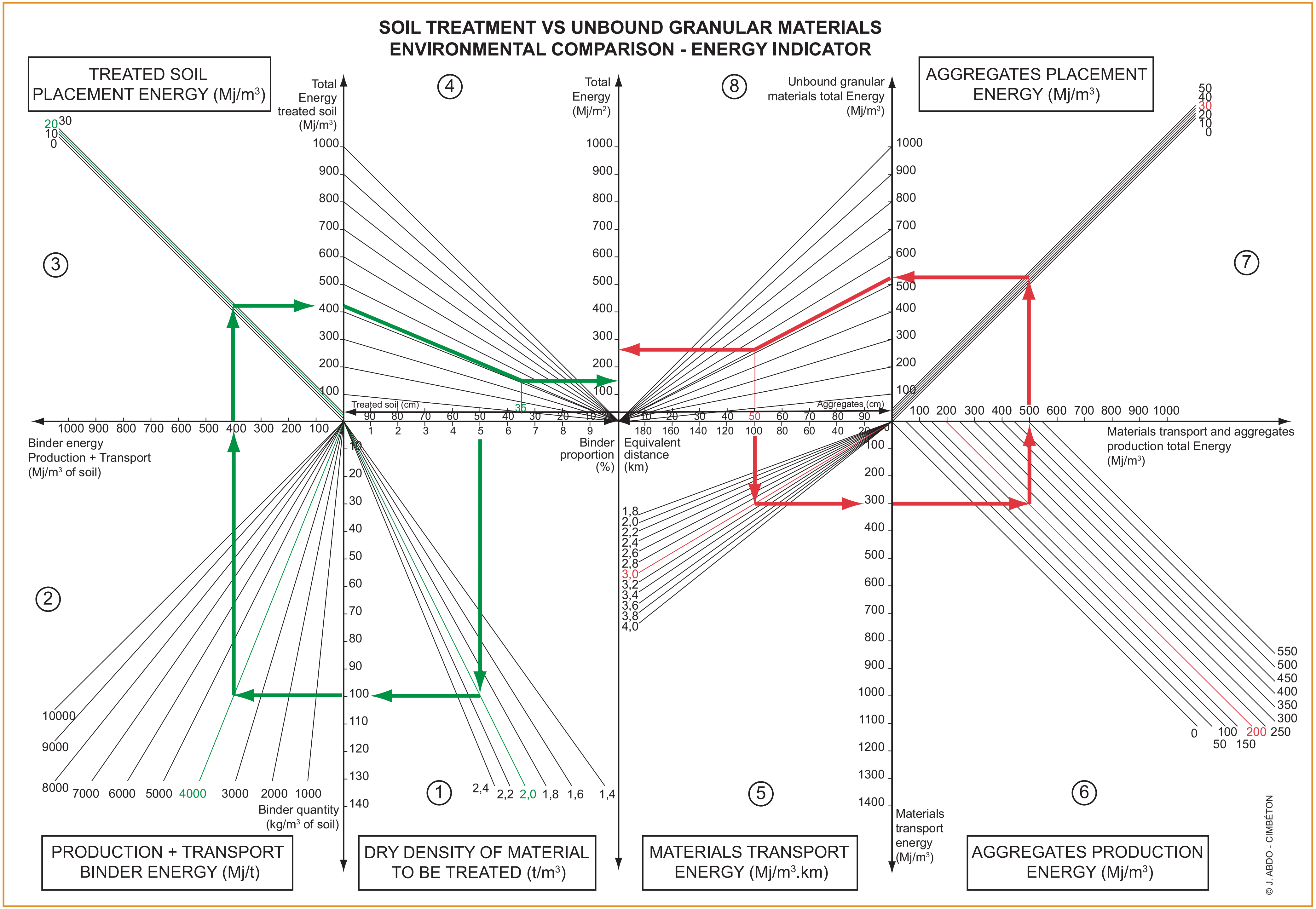


Figure 32: environmental comparison diagram (Energy) – Capping layers case



SOIL TREATMENT VS UNBOUND GRANULAR MATERIALS
ENVIRONMENTAL COMPARISON - ENERGY INDICATOR
TREATED SOIL PLACEMENT ENERGY (Mj/m³)
AGGREGATES PLACEMENT ENERGY (Mj/m³)
PRODUCTION + TRANSPORT BINDER ENERGY (Mj/t)
DRY DENSITY OF MATERIAL TO BE TREATED (t/m³)
MATERIALS TRANSPORT ENERGY (Mj/m³.km)
AGGREGATES PRODUCTION ENERGY (Mj/m³)
Total Energy treated soil (Mj/m³)
Total Energy (Mj/m²)
Unbound granular materials total Energy (Mj/m³)
Materials transport and aggregates production total Energy (Mj/m³)
Materials transport energy (Mj/m³)
Binder energy Production + Transport (Mj/m³ of soil)
Binder quantity (kg/m³ of soil)
Binder proportion (%)
Treated soil (cm)
Aggregates (cm)
Equivalent distance (km)
1
2
3
4
5
6
7
8
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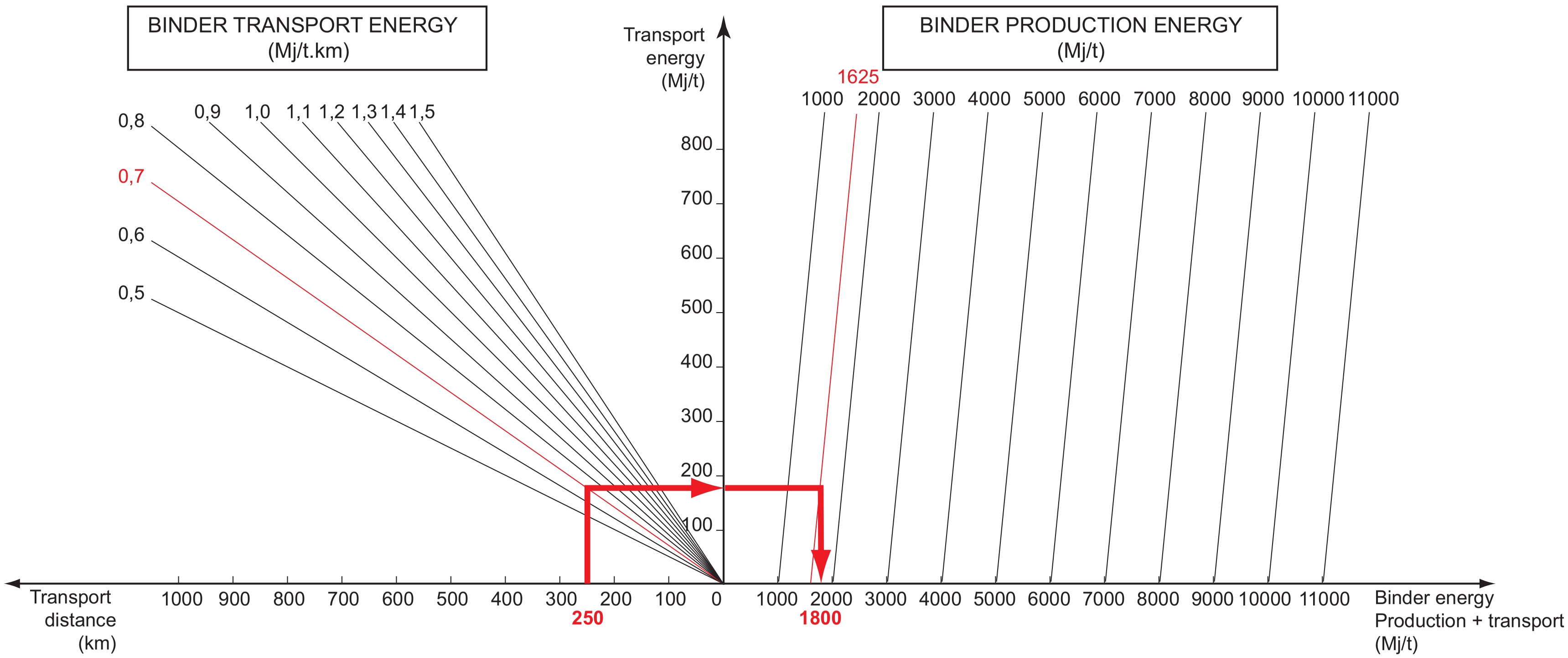
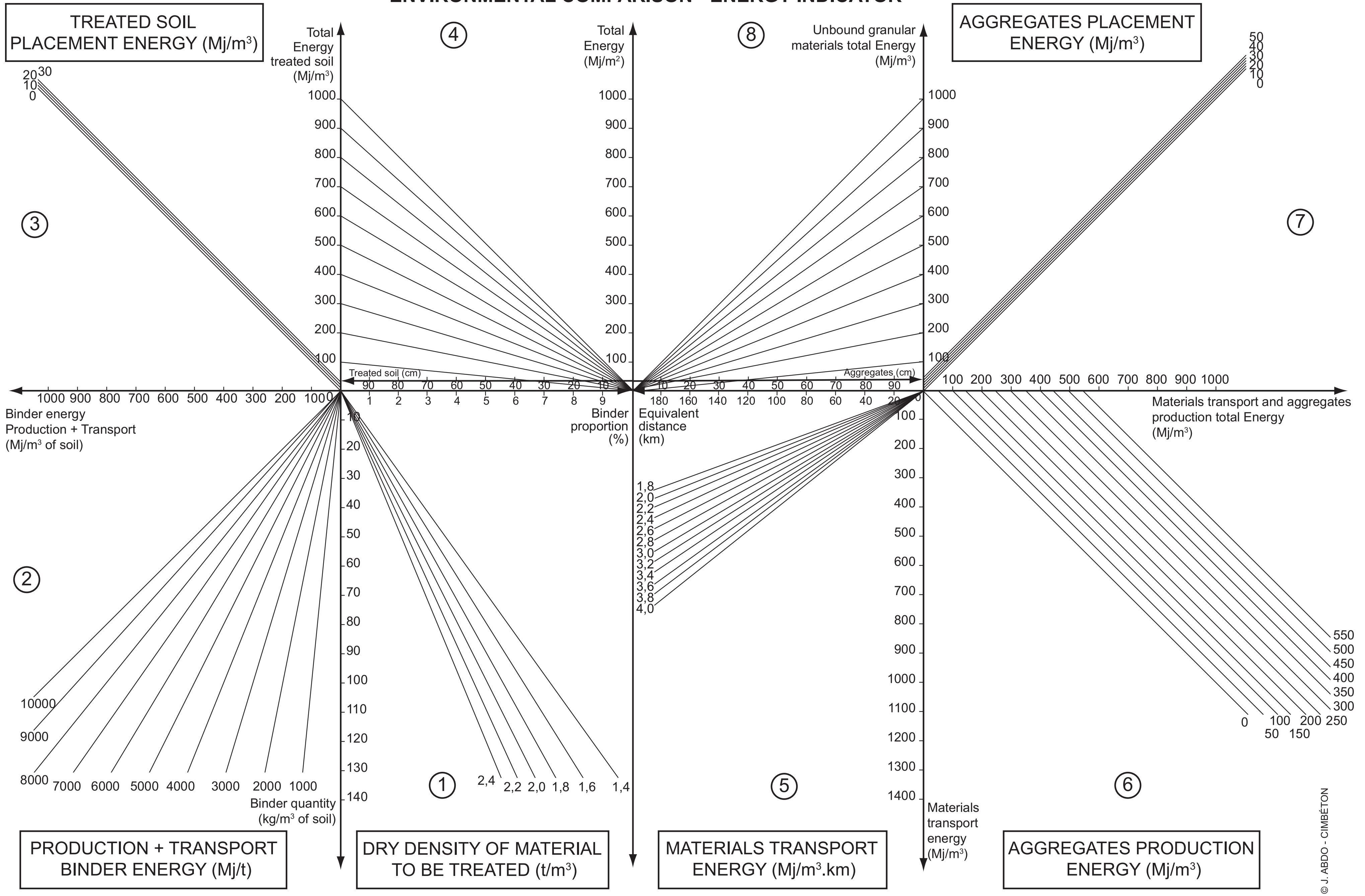
To make your own studies on Environment comparison – Energy indicator between the Soil treatment technique and the Unbound granular materials technique, you can simply photocopy the unmarked graph on page 52, add data specific to your study and read the result you need on the graph.

Diagram of evaluation of binder Energy (production + transport)



SOIL TREATMENT VS UNBOUND GRANULAR MATERIALS ENVIRONMENTAL COMPARISON - ENERGY INDICATOR



Chapter 4

Environmental comparison - CO_2 Indicator

4.1 - Study of Zone 1 – Soil treatment

This zone is divided into 4 quadrants numbered 1, 2, 3 and 4. Here are the main characteristics of each of these quadrants.

4.1.1 - Quadrant 1

It helps calculate the quantity of binder required per m^3 of soil to reach the performances required for the material treated, within the scope of the project under study.

In this quadrant is a family of straight lines (going through the origin) that represent various dry densities, corresponding to a wide range of materials that can be found in nature (figure 33).

Thus, for a given project, when the dry density of the soil and the binder proportion are known, we simply draw a descending vertical line going from the binder proportion digit to the intersection with the straight line of the dry density chosen: the binder quantity per m^3 of soil necessary for Soil treatment can then be read directly on the vertical axis of this Quadrant.

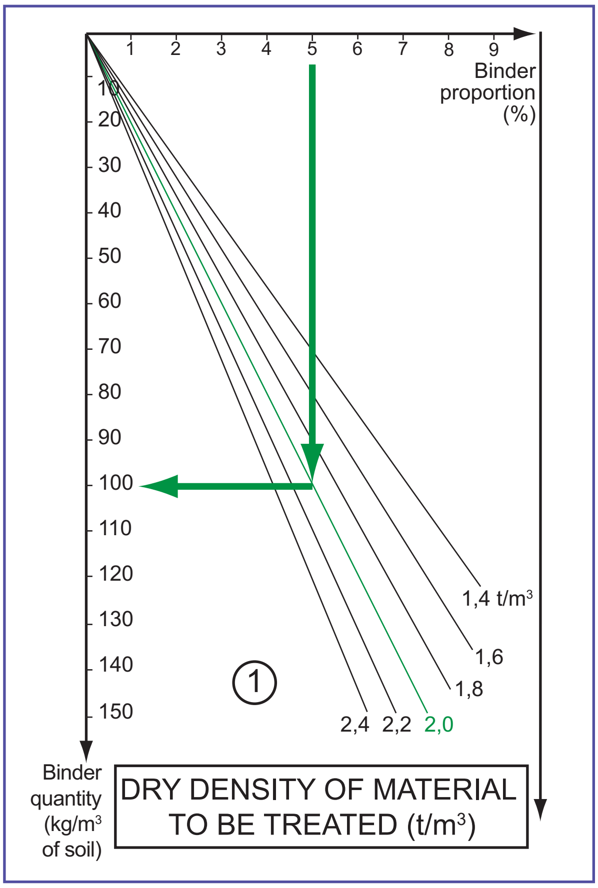


Figure 33: Soil treatment zone – Material dry density quadrant

If, for a given project, the nature of the material to be treated is known but not its dry density, refer to the indicative values of the table 6.

Materials	Dry density
Silt	**1,6 - 1,8**
Clay	**1,7 - 1,8**
Sand Homeometric sand Graduated sand	**1,4 - 1,9** 1,4 - 1,6 1,6 - 1,9
Granular soil	**1,8 - 2,2**

Table 6: dry density of different types of materials

4.1.2 - Quadrant 2

Once the binder quantity per m³ of soil has been determined by Quadrant 1, Quadrant 2 helps calculate its CO_2 impact.

In this Quadrant, we can see straight lines (going through the origin) which represent the CO_2 impact (expressed in kg CO_2 equivalent) of the various types of binders (figure 34).
So, for a given project, when the total CO_2 impact (production + transport) per ton of binder is known, we simply prolong horizontally the straight line of Quadrant 1 to the intersection with the straight line corresponding to the chosen impact: the CO_2 impact of binder per m³ of treated soil can then be read directly on the other axis of Quadrant 2.

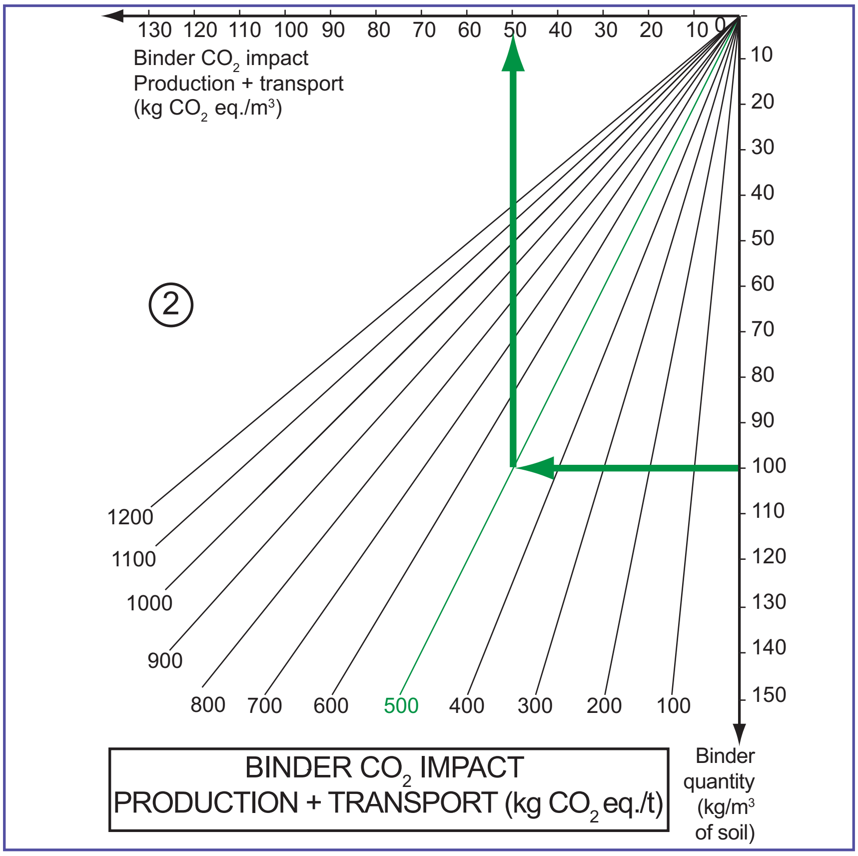


Figure 34: Soil treatment zone – Binder CO_2 impact quadrant

If the total CO_2 impact per ton of binder is not known or if the user wishes to accurately determine this impact with the local data at hand, he may refer to the diagram of figure 35.

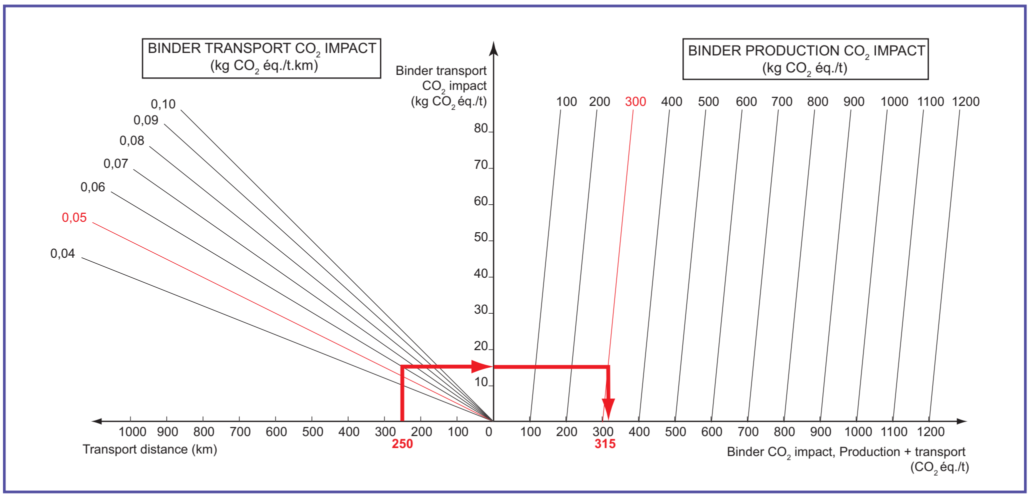


Figure 35: diagram of evaluation of binder CO_2 impact (production + transport)

Ce When the transport distance between the cement plant and the construction site is known, as well as the transport CO_2 impact in t.km and the CO_2 impact for production of a ton of binder, this diagram help determine, successively, the transport CO_2 impact and the total production + transport CO_2 impact.

The total CO_2 impact is then transferred on Quadrant 2, which will allow deducing the CO_2 impact per m^3 of treated soil.

4.1.2.1 - Transport CO_2 impact

When the transport CO_2 impact in t.km is not known, the user is able to calculate it using the following formula:

$$F(CO_2, D) = \frac{\textbf{Consumption per 100 km x 2.5}}{\textbf{Truck load capacity x 100}}$$

With:

Consumption per 100 km

16-ton truck: 29 litres of fuel

29-ton truck: 36 litres of fuel

40-ton truck: 40 litres of fuel

Truck load capacity

16-ton truck: 8-ton load capacity

29-ton truck: 16-ton load capacity

40-ton truck: 20-ton load capacity

Coefficient 2.5: his is the quantity of CO_2 equivalent (in kg) released by the combustion of a litre of fuel

Coefficient 100: for 100 km

4.1.2.2 - Binder production CO_2 impact

When the CO_2 impact per ton of binder is not known, we can use the values given as an indication in the table 7.

Binder	**CO_2 impact (kg CO^2 eq./t binder)**
CEM I	868*
CEM II	650*
Hydraulic Road Binder HRB 70% Slag	294*
Hydraulic Road Binder HRB 50% Slag	459*
Hydraulic Road Binder HRB 30% Slag	625*
Hydraulic Road Binder HRB 30% Limestone	614*
Hydraulic Road Binder HRB 30% Fly Ash	613*
Quicklime	1 059**

** Source: ATILH* *** Source: Union des Producteurs de Chaux*

Table 7: binder production CO_2 impact

To obtain the right CO_2 impact per ton of a given product, we invite you to contact directly the binder's producer.

4.1.3 - Quadrant 3

It relates to the CO_2 impact of placement.

In this Quadrant we see parallel straight lines that correspond to different hypothesis relating to the CO_2 impacts of placement equipment (spreader, mixer, sprinkler, compactor, grader).

These straight lines were drawn to include the combined CO_2 impacts of Quadrants 2 and 3: they are thus tilted by an angle of 45° and have ordinates at the origin equivalent to their own values (figure 36).

As the CO_2 impact value of the binder per m^3 of treated soil has been determined by Quadrant 2, we simply prolong vertically and upward the straight line obtained, to the intersection with the straight line that represents the CO_2 impact of placement equipment: the total combined impact per m^3 of treated soil can then be read directly on the other axis of Quadrant 3.

It is this value that will be considered in order to compare the total CO_2 impact of the Soil treatment technique and the total CO_2 impact of the unbound granular materials technique, for use in embankments.

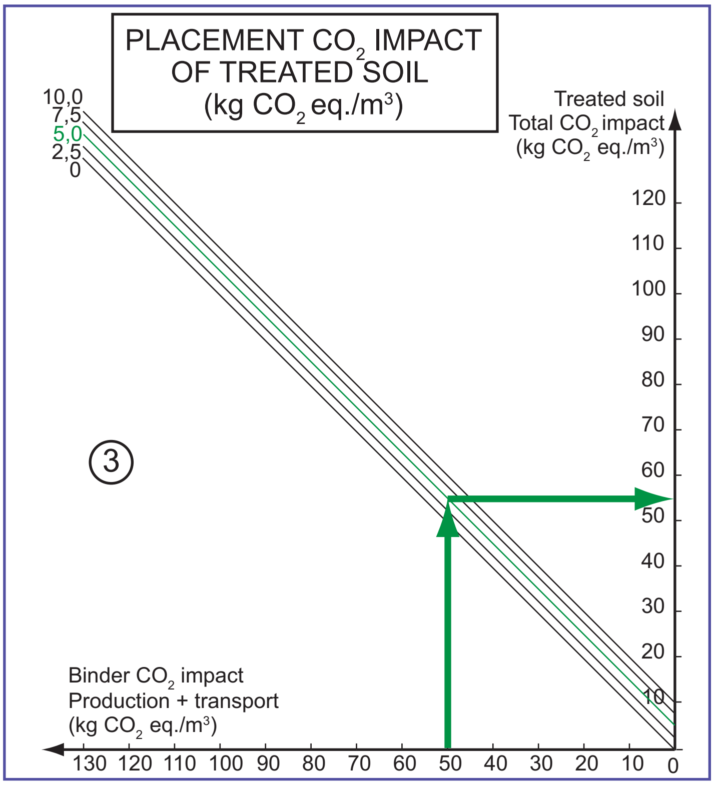


Figure 36: Soil treatment zone – Placement CO_2 impact quadrant

If the CO_2 impact of placement equipment is not known, we can use the following calculation method:

$$CO_2 \text{ Impact} = 2.5 \text{ L}$$

With:

CO_2 Impact: quantity of CO_2 equivalent for placement of a m^3 of treated soil (kg CO_2 equivalent)

Coefficient 2.5: quantity of CO_2 equivalent released by the combustion of a litre of fuel

L: fuel consumption of all equipment used for placement of treated soil (for 1 m^3). **L** values are given in the table 8.

L	Soil
0,7	Silty/sandy soil
0,8	Clay soil
0,9	Gravelly soil
1,0	Packed and difficult soil
> 1,0	Bouldery soil

Table 8: fuel consumption of all equipment used for treated Soil, according to soil nature

4.1.4 - Quadrant 4

Using a simple geometrical construction (Thales' theorem), this quadrant enables to go from the CO_2 impact per m³ of treated soil to the CO_2 impact per m² of treated soil (figure 37).

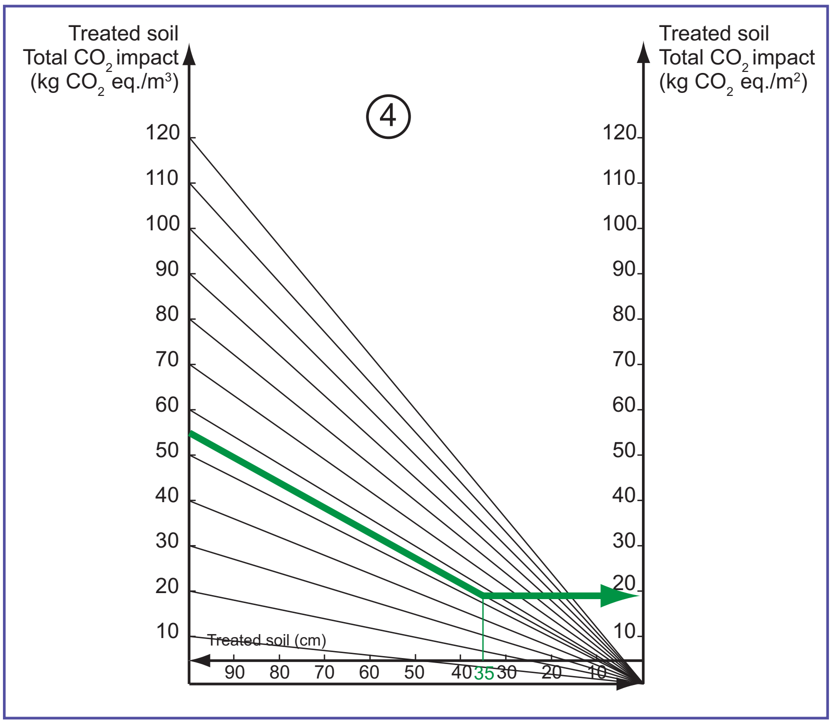


Figure 37: Soil treatment zone – Quadrant of total CO_2 impact (/m³ et /m²)

It is this value that will be considered to compare the total CO_2 impact of the Soil treatment technique and the total CO_2 impact of the unbound granular materials technique, for use in capping layers.

4.2 - Study of Zone 2 – Unbound granular materials

This zone is divided into 4 quadrants numbered 5, 6, 7 and 8. Here are the main characteristics of each of these quadrants.

4.2.1 - Quadrant 5

It measures the CO_2 impact of the following materials:
- Unbound Granular materials, from the quarry to the construction site,
- Surplus soil (whose volume is supposed, in this document, equivalent to that of unbound granular materials), from the construction site to the tip.

The straight lines of this Quadrant go through the origin and represent the CO_2 impact (expressed in kg CO_2 equivalent) of the various transport modes used (figure 38).
For a given project, knowing the distance between quarry and worksite as well as the distance between site and tip, we define an equivalent transport distance, i.e. the addition of quarry-site distance and site-tip distance. Once this equivalent distance is determined, and knowing the transport impact per m³.km, we use this Quadrant to read off the transport CO_2 impact per m³ of materials, as indicated by the red line on the graph below.

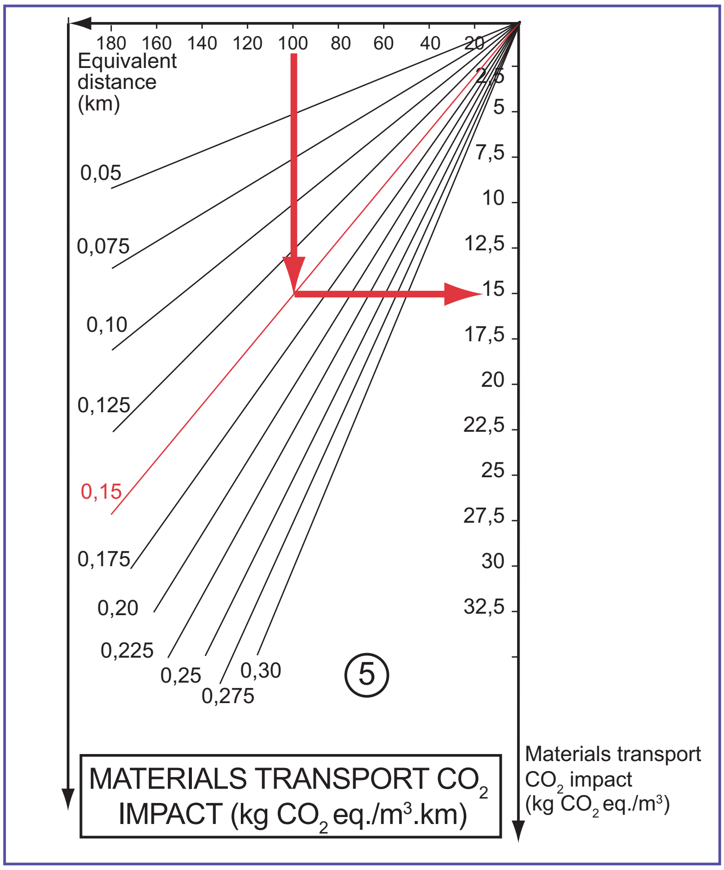


Figure 38: Unbound granular materials zone – Materials transport CO_2 impact quadrant

When the transport CO_2 impact per m³.km is not known, the user is able to calculate it using the following formula:

$$F(CO_2, D) = \frac{\text{Consumption per 100 km} \times 2.5 \times 2.2}{\text{Truck load capacity} \times 100}$$

With:

Consumption per 100 km
16-ton truck: 29 litres of fuel
29-ton truck: 36 litres of fuel
40-ton truck: 40 litres of fuel

Truck load capacity
16-ton truck: 8-ton load capacity
29-ton truck: 16-ton load capacity
40-ton truck: 20-ton load capacity

Coefficient 2.5: this is the quantity of CO_2 equivalent (in kg) released by the combustion of a litre of fuel

Coefficient 100: for 100 km

Coefficient 2.2: density of aggregates

4.2.2 - Quadrant 6

It measures the CO_2 impact of extraction and production for a m^3 of aggregates.

In this Quadrant we see several parallel straight lines, corresponding to the CO_2 impacts of various types of Unbound granular materials (rolled aggregate, crushed aggregate, hard rock, soft rock…).

These straight lines were drawn to include the combined CO_2 impacts of Quadrants 5 and 6: they are thus tilted by an angle of 45° and have ordinates at the origin equivalent to their own values (figure 39).

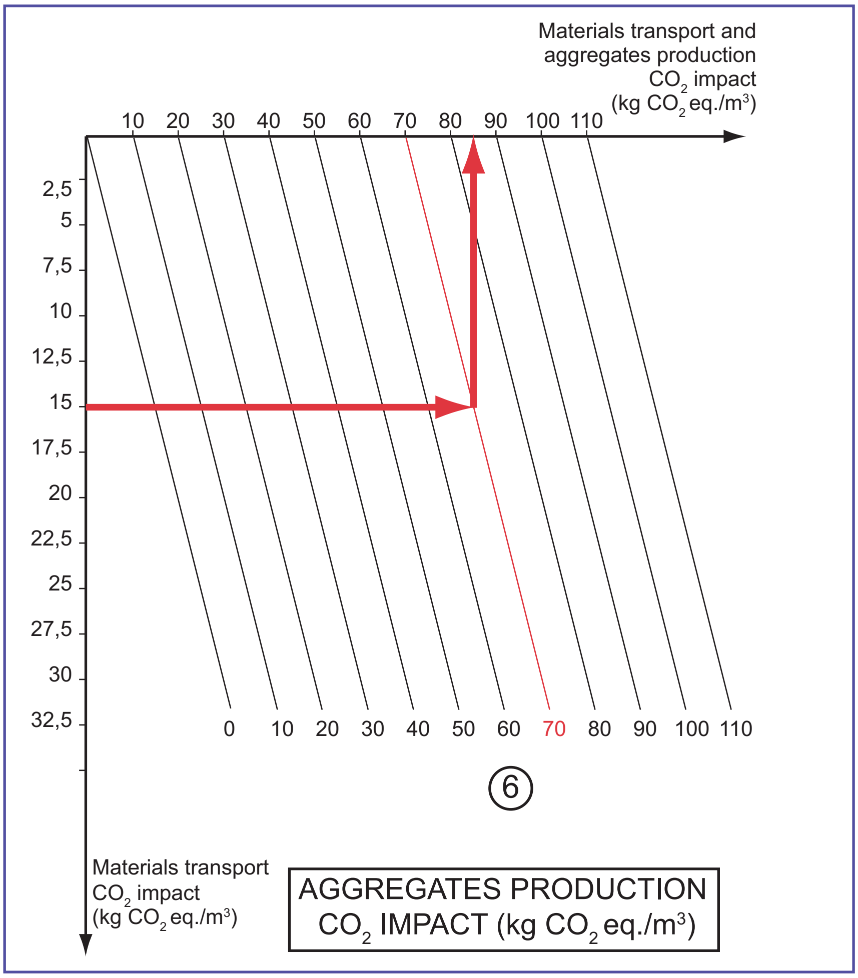


Figure 39: Unbound granular materials zone – Quadrant of aggregates extraction and production CO_2 impact

As the transport CO_2 impact has been determined at Quadrant 5 and as the extraction and production CO_2 impacts are known locally within the scope of this project, Quadrant 6 enables to calculate the combined CO_2 impact of materials transport and of extraction and production of aggregates.

4.2.3 - Quadrant 7

It measures placement CO_2 impact of Unbound granular materials.

In this Quadrant are parallel straight lines that correspond to different hypothesis relating to the CO_2 impacts of placement equipment (grader, sprinkler, compactor).

These straight lines were drawn to include the combined CO_2 impacts of Quadrants 5, 6 and 7: they are thus tilted by an angle of 45° and have ordinates at the origin equivalent to their own values (figure 40).

As the CO_2 impact of extraction, production and transport has been determined at Quadrant 6, and as the placement CO_2 impact is known locally within the scope of this project, Quadrant 7 enables to evaluate the combined total CO_2 impact for materials transport and for extraction, production, transport and placement of aggregates.

It is this value that will be considered in order to compare the total CO_2 impact of the Unbound granular materials technique and total CO_2 impact of the Soil treatment technique, for use in embankments.

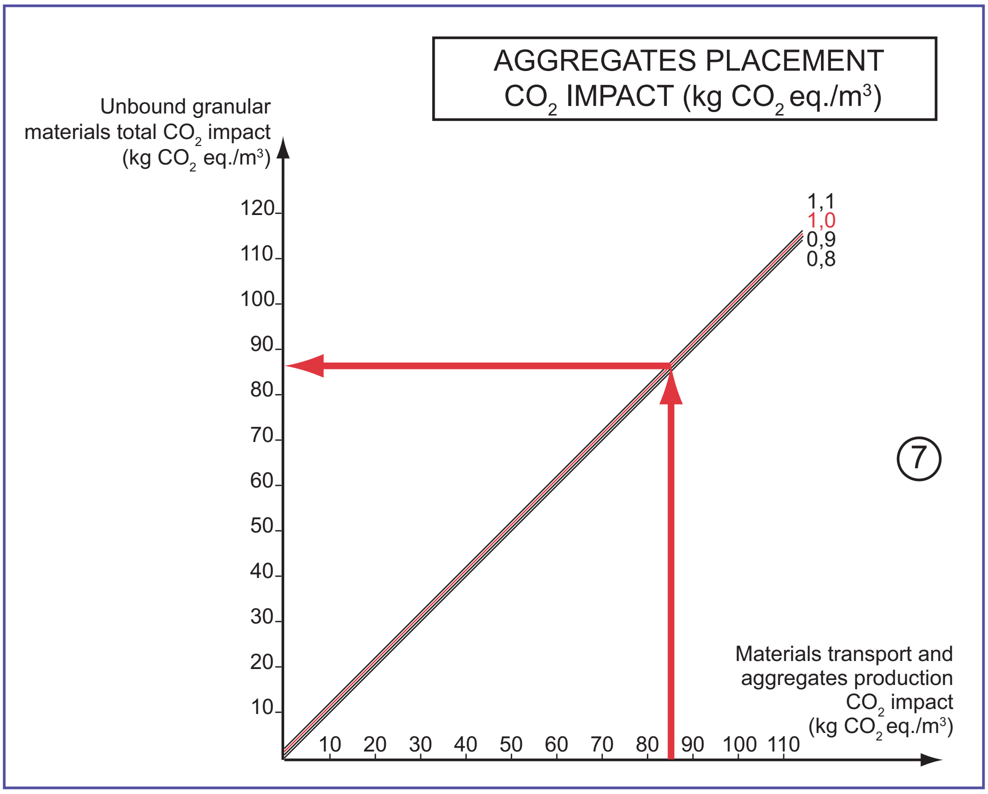


Figure 40: Unbound granular materials zone – Quadrant of aggregates placement CO_2 impact

■ *4.2.4 - Quadrant 8*

Using a simple geometrical construction (Thales' theorem), this quadrant enables to go from the CO_2 impact per m^3 of unbound granular materials to the CO_2 impact per m^2 of unbound granular materials (figure 41).

It is this value that will be considered to compare the total CO_2 impact of the unbound granular materials technique and the total CO_2 impact of the Soil treatment technique, for use in capping layers.

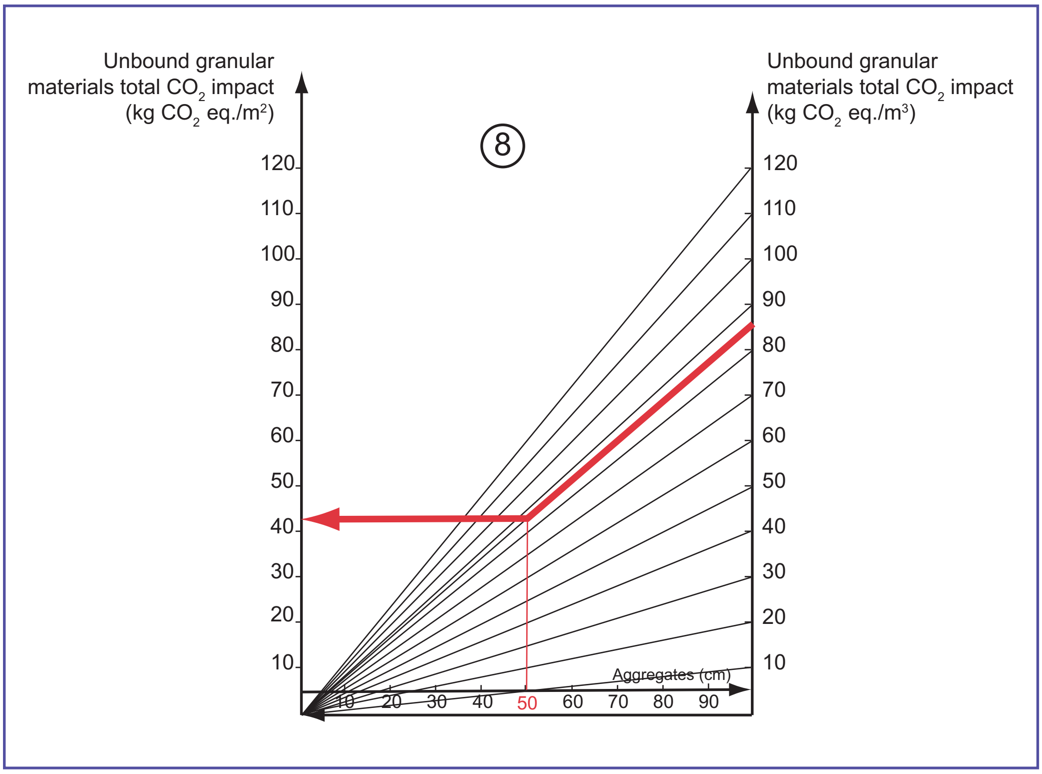


Figure 41: Unbound granular materials zone – Quadrant of total CO_2 impact (/m^3 et /m^2)

4.3 - Conclusion

By applying this method on the 4 Quadrants of Zone 1 and on the 4 Quadrants of Zone 2 we can compare the CO_2 impacts of the Soil treatment technique and the CO_2 impacts of the unbound granular materials technique.

For use in **embankments**, the comparison is made per m³ of material (figure 42).

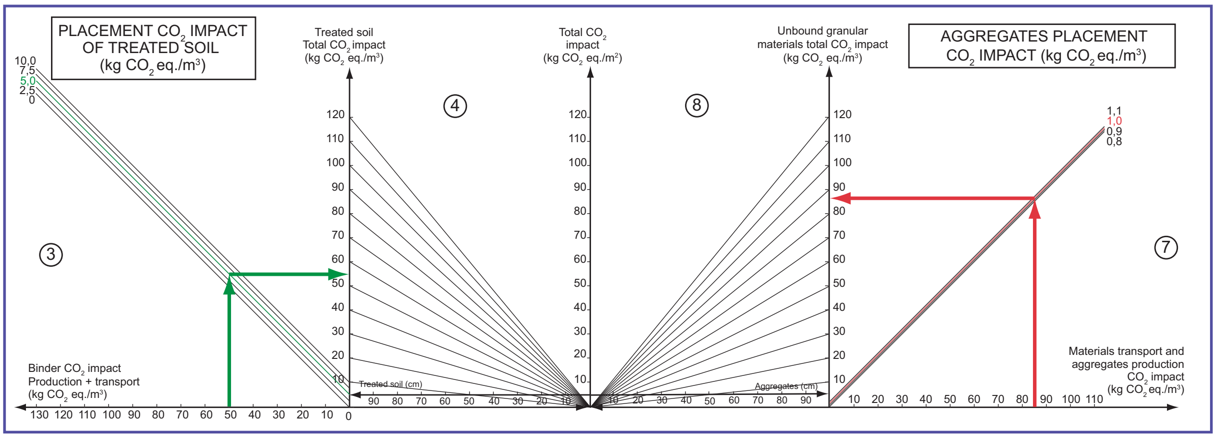


Figure 42: environmental comparison diagram (CO_2 impact) – Embankments case

For use in **capping layers**, the comparison is made per m² of material (figure 43).

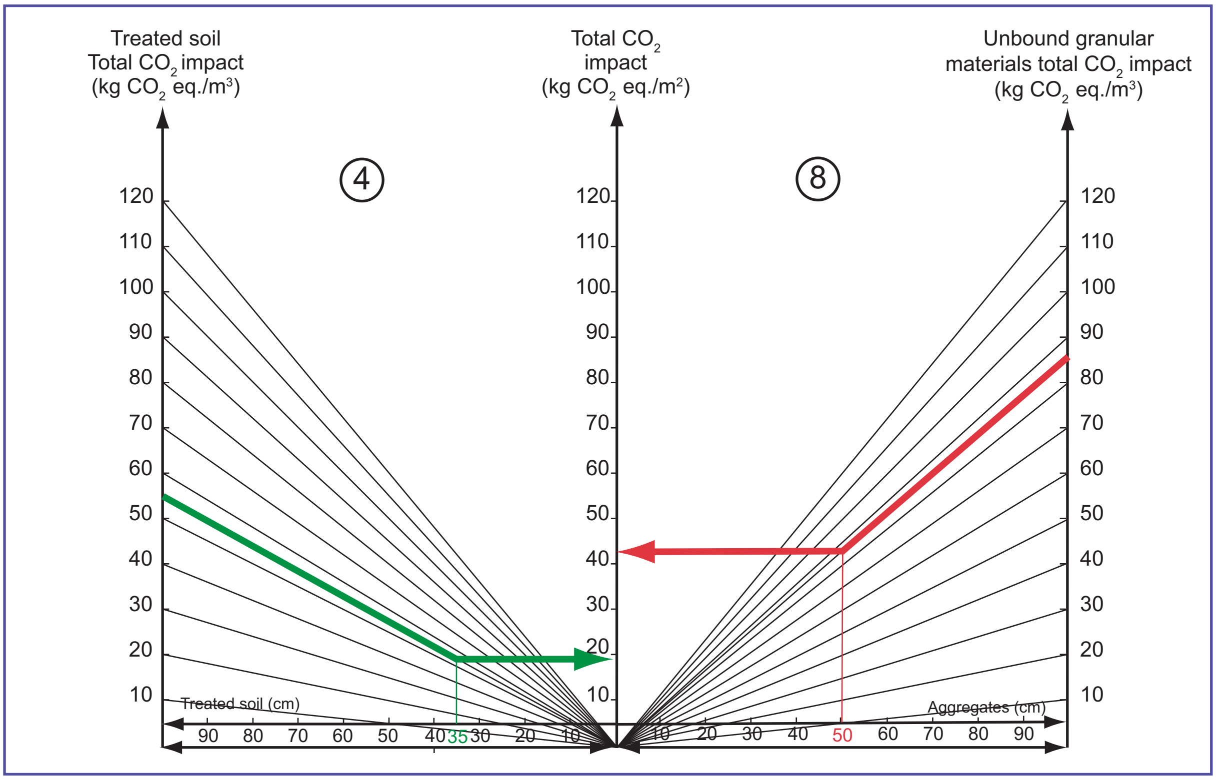
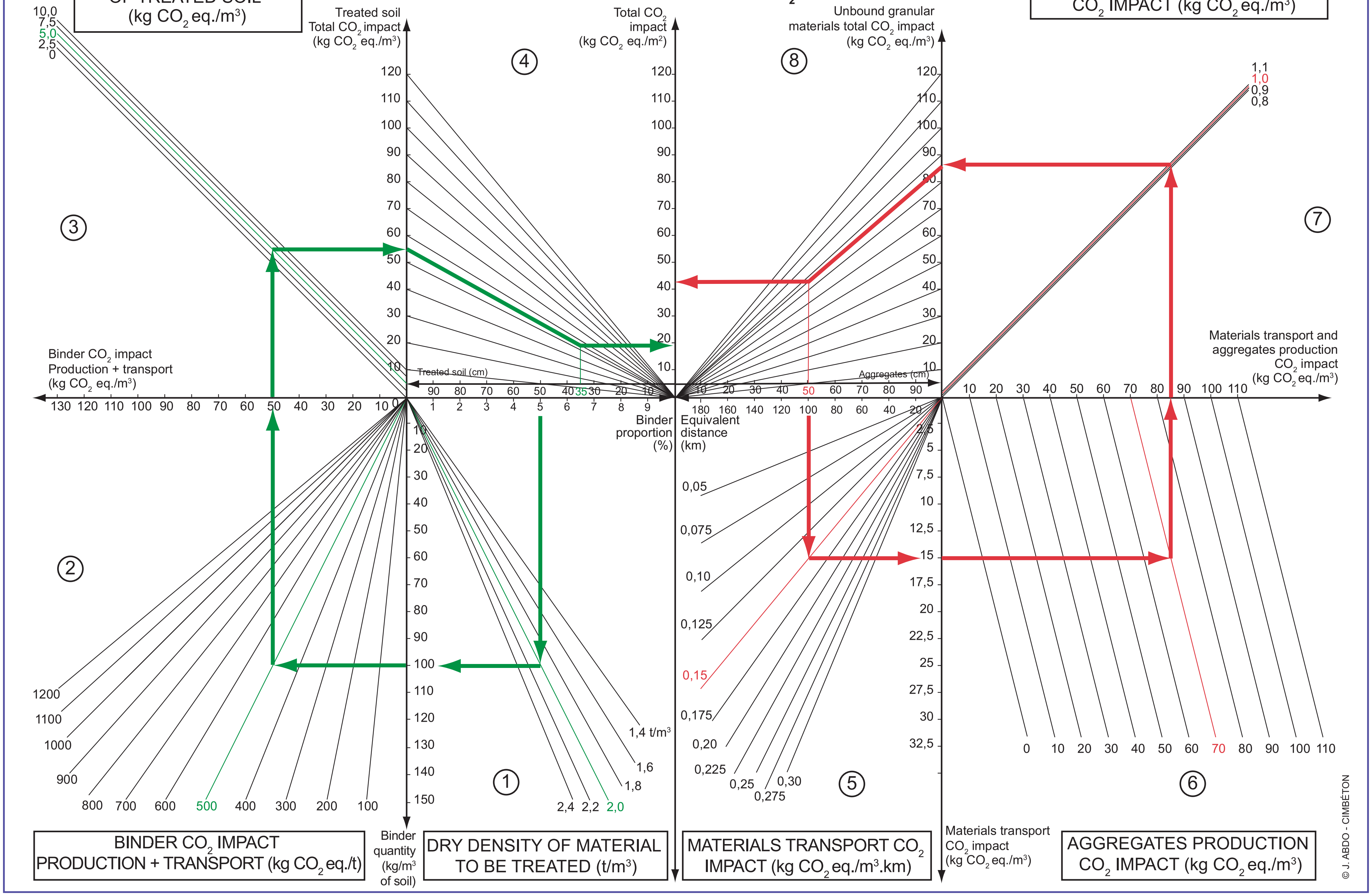


Figure 43: environmental comparison diagram (CO_2 impact) – Capping layers case

SOIL TREATMENT VS UNBOUND GRANULAR MATERIALS ENVIRONMENT COMPARISON - CO_2 INDICATOR



To make your own studies on Environment comparison – CO_2 indicator between the Soil treatment technique and the Unbound granular materials technique, you can simply photocopy the unmarked graph on page 69, add data specific to your study and read the result you need on the graph.

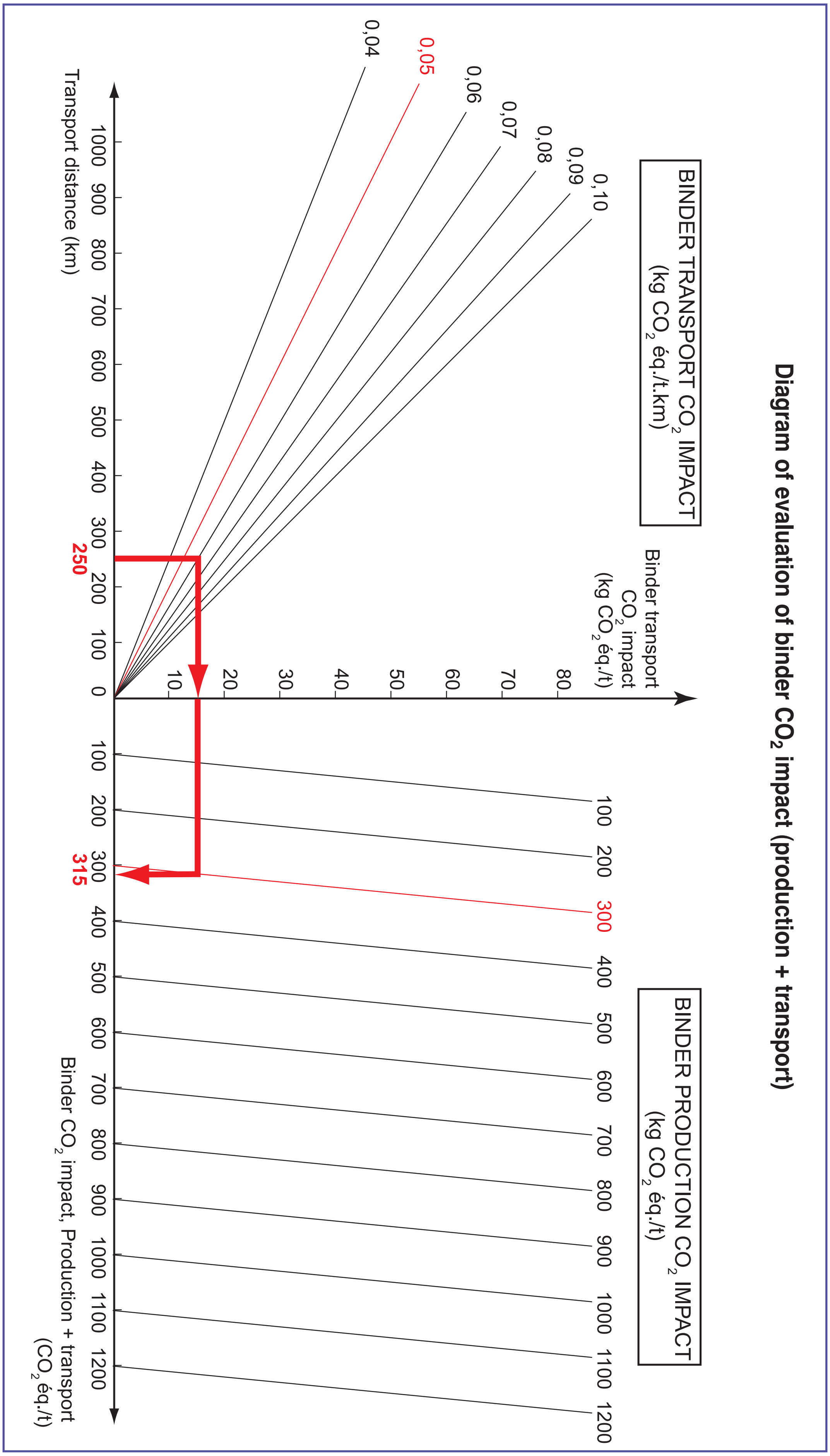
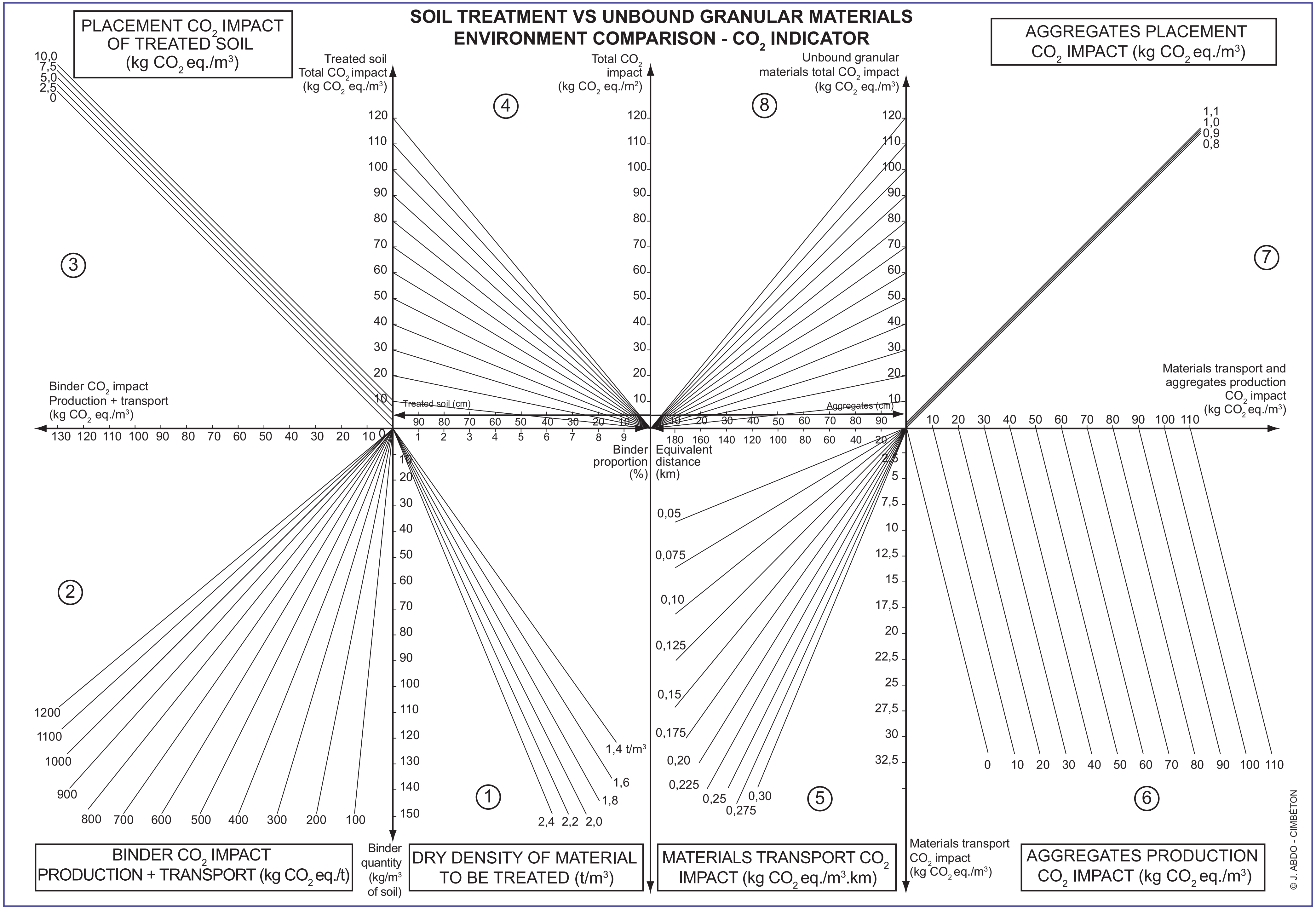


Diagram of evaluation of binder CO2 impact (production + transport)
BINDER TRANSPORT CO2 IMPACT
(kg CO2 éq./t.km)
0,10
0,09
0,08
0,07
0,06
0,05
0,04
Binder transport
CO2 impact
(kg CO2 éq./t)
10
20
30
40
50
60
70
80
Transport distance (km)
1000 900 800 700 600 500 400 300 200 100 0
250
BINDER PRODUCTION CO2 IMPACT
(kg CO2 éq./t)
100 200 300 400 500 600 700 800 900 1000 1100 1200
315
Binder CO2 impact, Production + transport
(CO2 éq./t)

SOIL TREATMENT VS UNBOUND GRANULAR MATERIALS ENVIRONMENT COMPARISON - CO_2 INDICATOR



Chapter 5

General conclusion

This study aims to offer a simple visual method that will help users make decisions as regards the choice of construction techniques, in the field of road earthworks.

It concerns the three impacts or indicators which are nowadays considered as most important: Economic, Energy and CO_2.

To supplement this study, other impacts or indicators may be studied in the future: water, natural resources, waste materials, acidification, eutrophication, ecotoxicity, human toxicity…

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