NUMERO: 2385A

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A P P U N T I

STUDENTE: Pirro Giulia

MATERIA: Construction of Roads Railways and Airport - Teori - Temi di Esame - Esercizi - Prof. Santagata

ROADS, RAILWAYS AND AIRPORTS

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2/10/16

Road :
- Natural profile
- Enbankment (made of soil)
- Pavment (specific layers of different materials)
  1) unbound (SCIOLTO) aggregats
  2) bituminus mixture
  3) portland cement concrete

select appropriatly e put correctly → choose material to obtain a long-life road

Soils
- Very variable (particels in different size and shape)
- Several materials
- Influenced by water
- Compaction (variation of volume)

Classification system
- Dimensions
- Attenberg's limits

Mechanic behavi
- Elastic : not dissipate energy (direct link between stress and deformations)
- Depends on loading conditions

1) Granular materials selected with specific properties (great variability of size)
↳ tipically used for foundations or railways (= same size)

Properties
- similar to soil
- extra requirement in term of shape and durability

2) Bituminus mixture (aggregate skeleton + binder (LEGANTE) ~ viscoelastic glue)
Properties
- long life
- flexible (deform without cracks)
- waterproof
- temperature and speed/time of loading sensitive

⟹ viscoelastic material

3) Cement paste (chimical reaction, not just a glue)
↳ rigid pavment (not very used)
↳ Airports
↳ it's more similar to an elastic material

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Master Course
in Civil Engineering
2017-18

Costruction of Roads, Railways and Airports (01RVMMX)

GENERALITIES
Technical Specifications
Quality control / Quality assurance

General overview

Phases of design and construction of transportation infrastructures

Analysis of feasibility
- Pre-feasibility study
- Feasibility study

Design
- Preliminary design
- Final design
- Executive design

Construction
- Award of contract
- Execution of works
- Measurements and accounting

Final acceptance

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Specifications

Technical specifications contains informations about these three themes:

Characterization and qualification of component materials
→ qualify for the purpose (=acceptance)

Construction and placement of materials
→ produce and place

Control during construction and on completed works (QC/QA)
quality control
quality assurance program

Reference to relevant standards.

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Specifications

Technical specifications

- **PRESCRIPTIVE**
- **PERFORMANCE-BASED**

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Specifications

Technical specifications

➢ PRESCRIPTIVE vs PERFORMANCE-BASED

Performance-based specifications have the advantage/disadvantage of reducing the work of the Engineer (no need of continuous testing) and in giving the Contractor freedom in defining the most profitable working strategies.

Performance evaluation eliminates the risk of litigations during construction due to the different interpretation of prescriptive Specifications.

Best option: "hybrid" approach.

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Specifications

Technical specifications

➢ PRESCRIPTIVE vs PERFORMANCE-BASED

Performance-based specifications require the use of parameters which derive from advanced investigation techniques (e.g. simulative full-scale testing, mechanistically-based laboratory tests).

Mechanistically-based laboratory tests

Full-scale field testing (FWD, structural)

Full-scale field testing (SCRIM, functional)

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Quality Control (QC) and Quality Assurance (QA)

Variability of characteristics of materials and works

Total variability is the sum of several components

- Sampling campionatura
- Experimental tests
- Materials
- Construction (production and placement)

$$S^2_{QC/AC} = S^2_c + S^2_l + S^2_{m/c}$$

Total Variability = $\underbrace{\text{sampling + laboratory}}_{\text{they have to be minimized, reduced as much as possible}}$ + material/construction

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Quality Control (QC) and Quality Assurance (QA)

Variability of characteristics of materials and works

Sampling →	random variability linked to procedures for selection of samples
Experimental tests →	random variability linked to laboratory procedures

- Can cause more than 50% of total variability
- It is fundamental that operators tightly respect procedures

Materials / Construction ⟹ Natural variability of the characteristics of materials and production/placement operations

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Quality Control (QC) and Quality Assurance (QA)

Terminology

used for tests

- **Precision** = low variability of measurements repeated in control conditions
- **Accuracy** = conformity of result with respect to true value

Good measurement precision, low accuracy

Low measurement precision, good accuracy

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Quality Control (QC) and Quality Assurance (QA)

Statistical parameters

they have the unite measure of the quantity

- **Average**
- **Median value**
- **Variation range**
- **Variance**

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Quality Control (QC) and Quality Assurance (QA)

Coefficient of variation

Defines the degree of variability of measurements

$$CV = \frac{\sigma}{\bar{x}} \cdot 100$$

< 2% = very low variability
2 – 5% = low variability
5 – 10% = moderate variability
10 – 20% = high variability
> 20% = very high variability

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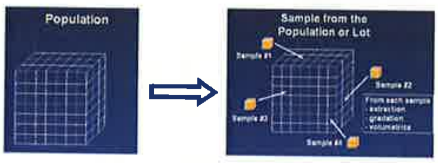
Quality Control (QC) and Quality Assurance (QA)

Sampling criteria

Determination of a given characteristic referred to a quantity of product (lot) popolazione should be performed on a limited number of samples



REPRESENTATIVE OF THE ENTIRE LOT

SAMPLING PROGRAM

- Test frequency (when)
- Location of samples (where)
- Size of samples (number)

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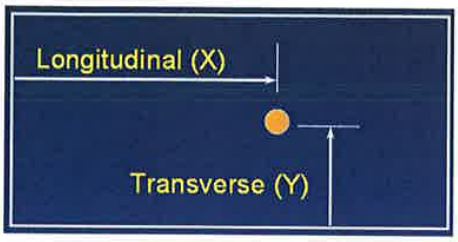
Quality Control (QC) and Quality Assurance (QA)

Generation of random positions



A locl system of cartesian coordinates is define for each sub-lot

Sub 1	Sub 2	Sub3	Sub 4		
74	60	01	27	43	X
29	21	78	01	43	Y
28	37	00	49	97	
73	08	87	32	97	
72	14	09	70	41	

A random sequence of numbers is generated

↳ they become coordinates of random positions

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Quality Control (QC) and Quality Assurance (QA)

Generation of random positions

Generated numbers are multiplied by the transversal dimension of the sub-lot

Exeample ⟶ Rectangular shape 100 m x 12 m

Sub-lot 1

- Coordinate X = 0,74 x 100 = 74 m
- Coordinate Y = 0,29 x 12 = 3,5 m

Sub-lot 2

- Coordinate X = 0,60 x 100 = 60 m
- Coordinate Y = 0,21 x 12 = 2,5 m

... etc.

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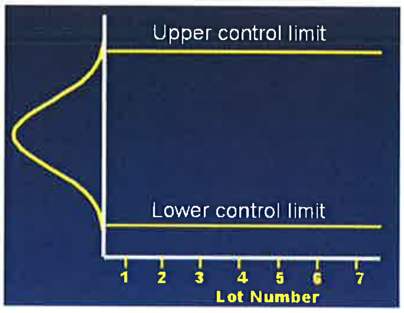
Quality Control (QC) and Quality Assurance (QA)

CONTROL CHARTS – Usage criteria

It can be considered as a sequence of normal distribution curves (vertical axis) as a function of tested samples (lots)



It can be assumed that the process is "under control" when the values are contained within the upper and lower limits

⇓

Average ± 3 σ

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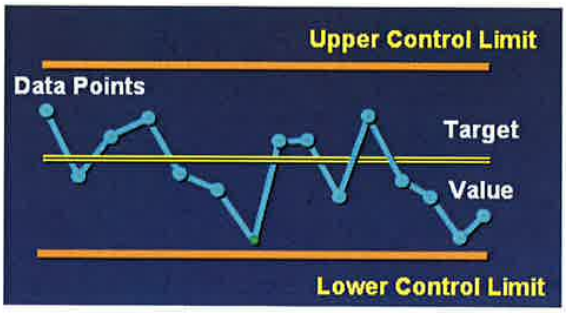
Quality Control (QC) and Quality Assurance (QA)

CONTROL CHARTS – Usage criteria

A fundament characteristic of this approach is the possibility of distinguishing random variability from systamic variability due to a specific cause



sometimes there is only a limit (not both the upper and the lower)

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Quality Control (QC) and Quality Assurance (QA)

CONTROL CHARTS – Interpretation

There is a problem (the system is not under control any more) when:

↳ the best solution is when $\bar{X}$ and R are whitin the average

- $\bar{X}$ varies, R constant
- $\bar{X}$ constant, R varies
- $\bar{X}$ e R vary

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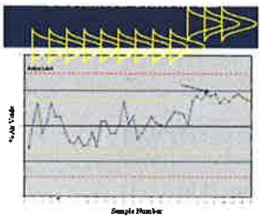
Quality Control (QC) and Quality Assurance (QA)

CONTROL CHARTS – Interpretation

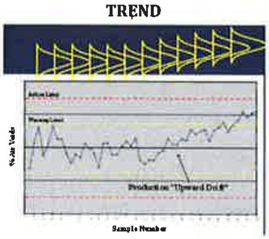
Example: Variation of average

ABRUPT CHANGE



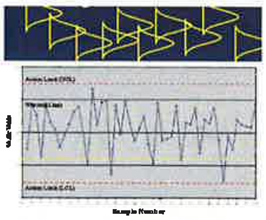
Ex. Abrupt failure

TREND



Ex. Progressive wear

IRREGULARITY



Ex. Continuous non necessary adjustments

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Quality Control (QC) and Quality Assurance (QA)

QUALITY INDEXES

$$Q(U)=\frac{USL-\overline{X}}{\sigma}$$

$$Q(L)=\frac{\overline{X}-LSL}{\sigma}$$

Parametrs P_U or P_L (AASHTO)

VARIABILITY – UNKNOWN PROCEDURE
STANDARD-DEVIATION METHOD

Quality Index (Q_U or Q_L)	Percent Within Limits for Selected Sample Sizes							
	N = 3	N = 4	N = 5	N = 6	N = 7	N = 8	N = 9	N = 10
1.50	100.00	100.00	96.20	95.19	94.72	94.44	94.26	94.13
1.55	100.00	100.00	97.13	96.00	95.48	95.17	94.97	94.82
1.60	100.00	100.00	97.97	96.75	96.17	95.84	95.62	95.46
1.65	100.00	100.00	98.72	97.42	96.81	96.45	96.22	96.05
1.70	100.00	100.00	99.34	98.02	97.38	97.01	96.76	96.59
1.75	100.00	100.00	99.81	98.55	97.89	97.51	97.25	97.07
1.80	100.00	100.00	100.00	98.99	98.35	97.96	97.70	97.51
1.85	100.00	100.00	100.00	99.36	98.74	98.35	98.09	97.91
1.90	100.00	100.00	100.00	99.65	99.07	98.69	98.44	98.25
1.95	100.00	100.00	100.00	99.85	99.35	98.99	98.74	98.56
2.00	100.00	100.00	100.00	99.97	99.57	99.24	99.00	98.83
2.05	100.00	100.00	100.00	100.00	99.74	99.45	99.23	99.06
2.10	100.00	100.00	100.00	100.00	99.86	99.61	99.41	99.26
2.15	100.00	100.00	100.00	100.00	99.94	99.74	99.57	99.42
2.20	100.00	100.00	100.00	100.00	99.99	99.84	99.69	99.56
2.25	100.00	100.00	100.00	100.00	100.00	99.91	99.79	99.68
2.30	100.00	100.00	100.00	100.00	100.00	99.96	99.86	99.77
2.35	100.00	100.00	100.00	100.00	100.00	99.98	99.92	99.84
2.40	100.00	100.00	100.00	100.00	100.00	100.00	99.95	99.89
2.45	100.00	100.00	100.00	100.00	100.00	100.00	99.98	99.93
2.50	100.00	100.00	100.00	100.00	100.00	100.00	99.99	99.96
2.55	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.98
2.60	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.99
2.65	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

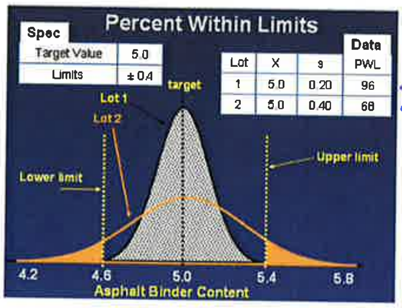
Numbers in the body of this table are estimates of percent within limits (PWL) corresponding to specific values of Q, the QUALITY INDEX. For Q values less than zero, subtract the table value from 100.

NOTE: More detailed tables (ΔQ = 0.01) can be developed from more accurate values of PWL.

AASHTO QC/QA Guide Spec. Page 21

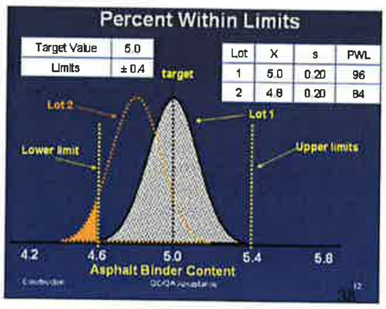
Quality Control (QC) and Quality Assurance (QA)

ACCEPTANCE – PWL



Same average, different degree of dispersion

cv =0,04
cv =0,08



} less difference

Same standard deviation, different average value

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Construction of Roads, Railways and Airports (01RVMMX)

all those activities related with soil (natural element)

EARTHWORKS – SOILC

Classification, compaction, bearing capacity

it has to be understood because it isn't a human product

First we have to understand soil
in general linked with water (it is generally partial saturated)

General concepts on earthworks

even if it's related to railways and airports too

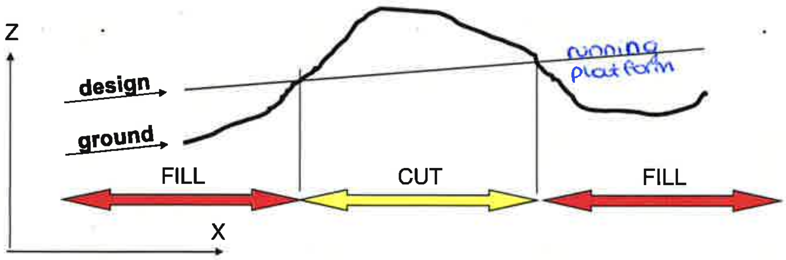
Road prism (SOLIDO STRADALE)
longitudinal element — on the bottom

Cross section delimited by road platform (including marginal elements), originary ground and lateral slopes. on the sides

at the top

Obtained by means of earthworks with the cutting of trenches and construction of embankments.

Earthworks are also supplementary applications which require movement of soil



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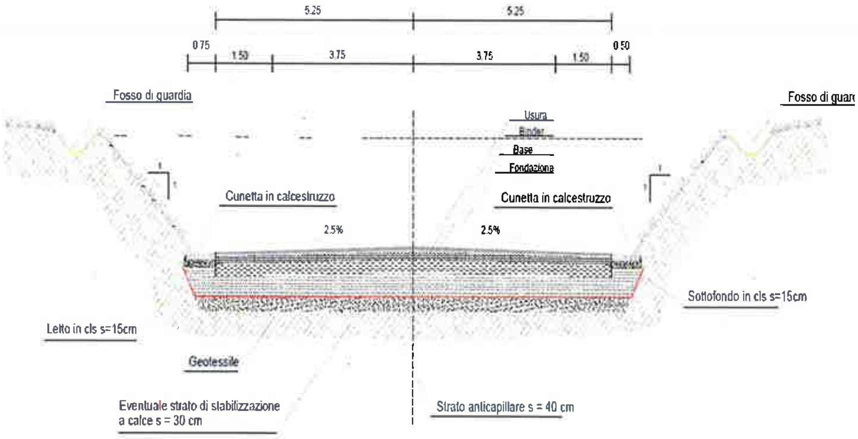
05/10/2017

General concepts on earthworks

Road prism

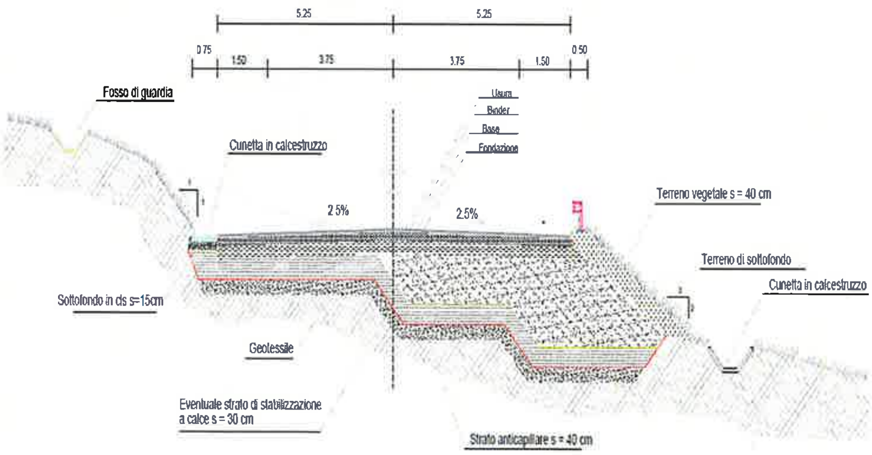
CUT SECTION



General concepts on earthworks

Road prism

CUT AND FILL SECTION → in one portion we need to add soil in the other one to cut it.



falda: water table (its position is necessary to be defined)
capillary fringe is nearly upon to the water table

maybe we can use pipes to drain out the water and have a drier condition in the upper part of the soil → problems exist also if the water table is too deep

↳ because it could lead to problems for foundations if water table is to high

SOIL

RICHIAMI

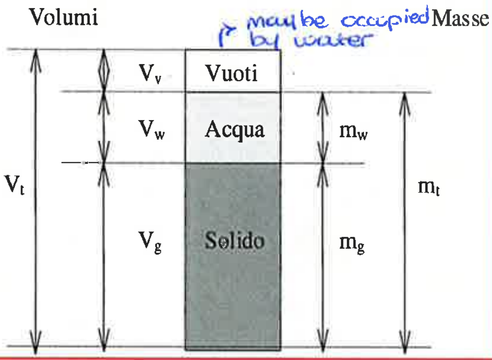
Soils are formed from several alteration processes:

- physical (decompression)
- chemical (action of O_2, CO_2, acids)
- organic (acids, bacteria)
- mechanical (erosion, impact)

↳ infinite multitude of possible soils

Three-phase system

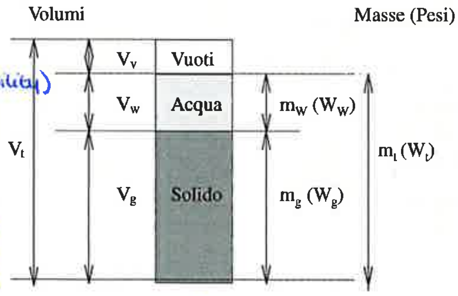
SOLID + LIQUID + AIR



SOIL

RICHIAMI

Definitions



- Water content — not an intrinsic property (it changes) (state variability)

$$w[\%]=\frac{W_w}{W_g}\cdot 100=\frac{W-W_g}{W_g}\cdot 100$$

- Grain density

$$\gamma_g=\frac{W_g}{V_g}$$

→ Archimede's principle leads to the volume (it could be measured)

- Apparent density

$$\gamma=\frac{W}{V}=\frac{W_w+W_g}{V_g+V_v+V_w}$$

- Dry density

$$\gamma_s=\frac{W_g}{V}=\frac{W_g}{V_g+V_v+V_w}$$

↳ used in analysis of compaction

- Void index — use for consolidation theory

$$e=\frac{V_v+V_w}{V_g}$$

- Porosity

$$n=\frac{V_v+V_w}{V}$$

SOIL

RICHIAMI

Capillarity

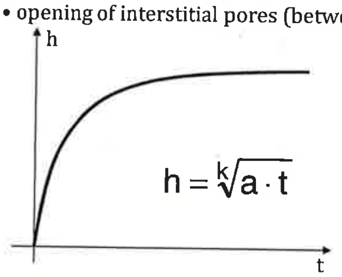
water can move in an unsatured soil (water naturally goes through capillaries)

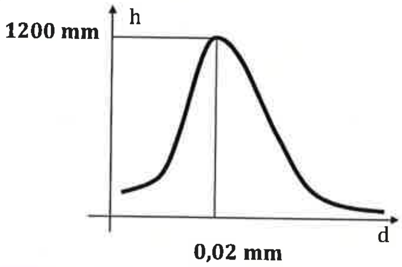
In unsaturated soils capillarity tensions can occur and these may cause the upward motion of water.

The height by which free water can move upwards by capillarity (h) depends upon:

- time;
- opening of interstitial pores (between grains).

there is a perfect dimension of poors in which we can have capillary movement





SOIL

RICHIAMI

→ there is a depth in which it could happen

Frost effects (depends on the general climate)

↳ increase of water volume

Effect of low temperatures (T<0°C) in the winter period:

- formation of ice lenses (volume increase);
- expansion;
- spring thaw with vlume eduction and loss of bearig capacity.

Conditions:

- soil size distribution;
- position of water table;
- climatic conditions (depth of frost penetration).

09/10/2017

SOILS

The dimensions of particels influence mechanical properties (mass or surface forces)

REVIEW

Physical and mechanical properties

Soil behaviour depends upon: (external factors ex loading but internal ones too)

internal factors
- size distribution of particles;
- presence of water and sensitivity which particles have in interacting with it.

On representative soil sample the following aspects are evaluated:

- percentage of size fractions,
- sensitivity to water (of finer fractions).
  ↳ that soil has changing water content

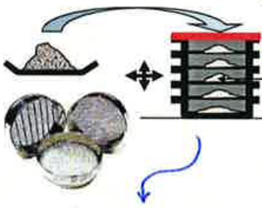
SOILS

REVIEW

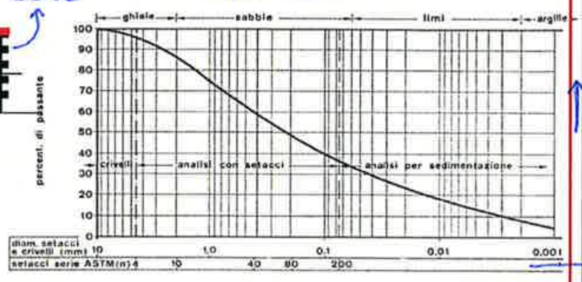
it has to be wet because the analysis has to be realistic (it creates lumps) GRUMO

Analysis of particle size distribution (granulometry)
↳ not used

seive



particels tend to move down



percent passive

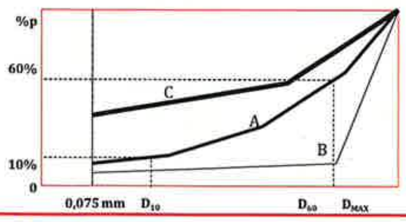
size of particels } equivalent opening of the size

Uniformity coefficient:

D_{60}/D_{10}

↑ : Less uniform soil
↳ more distributed

↓ : More uniform soil
↳ problem in compacting



central part of the distribution

SOILS → sensitivity of water is linked to fine fraction

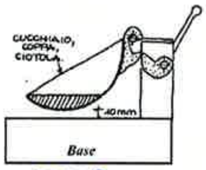
Liquid limit – methods of measurement

determined empirically

Tests carried out on material **passing at the 0.425 mm sieve**. including fine part of sand

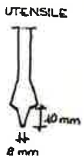
LL – Liquid limit (Casagande apparatus)

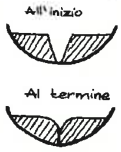
may have significant interaction with water



spoon bouncing on a table

OLD METHOD

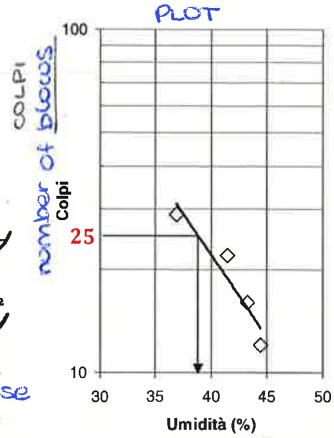




the cut will close

number of blows to close it

SEMI-LOGARITICM PLOT



this procedure is quite sentitive to the operators even if it's simple

SOILS (European community and USA)

Liquid limit – methods of measurement

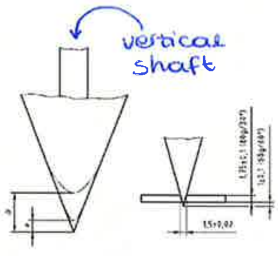
UNI CEN ISO/TS 17892-12:2005

Tests carried out on material **passing at the 0.425 mm sieve**

Cone penetrometer

similar to the one used for bitchment test

NEW METHOD



Two geometries:

- 60g/60° — 60 degrees of cono
- 80g/30°

Two different procedures

SOILS

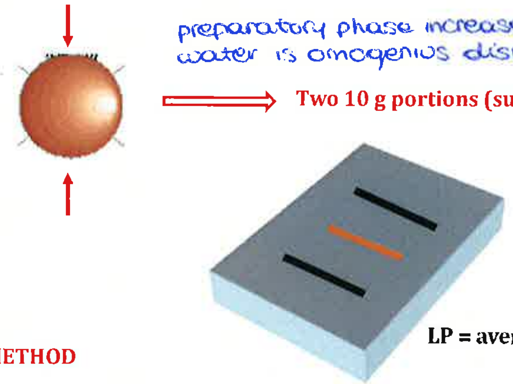
Plastic limt – methods of measurement => prepare a small ball

UNI CEN ISO/TS 17892-12:2005

20 g of moist soil

preparatory phase increase the reliability of test: water is omogenius distributed

Two 10 g portions (sub-samples)



LP = average of two repetitions

NEW METHOD

SOILS

Classification of soils (different methods but has to satisfy some requisites)

It is a tool for the prelimienary evaluation of soil performance based on particle size and sensitivity to water.

Requisites:

- clear meaning of considered parameters;
- easy and quick determination of results; in real time even during construction (IMPORTANT!)
- simple equipment which can be used in field laboratories;
- parameters which do not depend on soil state (wet or dry), on stress conditions and environmental conditions. has to be linked to intrinsec properties, not external ones

⇓

ALLOWS THE DISTINCTION BETWEEN SOILS WHICH CAN BE USED FOR EARTHWORKS AND THOSE WHICH MAY NOT

←

SOILS

Classification of soils – HRB system (UNI 11531-1:2014)

PRIORITY OF USE (general)

- Groups A1, A2-4, A2-5, A3;
- Groups A2-6 and A2-7. (intermediate level)

For soils belonging to groups A4, A5, A6 and A7 it should be considered whether:

- to use the with proper attention (protection from water);
- to proceed with treatment/improvement (e.g. lime stabilization), CALCE VIVA
- to exclude their use and proceed with disposal.

SOILS

Classification of soils – HRB system (UNI 11531-1:2014)

PRIORITY OF USE (specific)

- **EMBANKMENT**: Groups A1, A3 (confined, if necessary), A2-4, A2-5, A4 (with group index equal to 0), A2-6, A2-7 (lower part of embankment, at least at 2 m from pavement support level, with anti-capillary layer);
- **SUBGRADE**: Groups A1, A2-4, A2-5, A3 (with uniformity coefficient greater than 7); ↳ top of the embankment (premium quality soil) or the cut section
- **RAILWAY EMBANKMENTS**: Groups A1, A2-4, A2-5, A2-6, A2-7, A3 (depending upon particle size distribution), A4 for embankment
- **RAILWAY SUBGRADE**: Groups A1, A2-4 e A3 (depending upon particle size distribution)

same kind of sand settle after vibration which can be produced by railway

SOIL COMPACTION

Goals of compaction

we don't want the soil densify during the use
- reduce further settlements during service life of infrastructure as a result of static loads (permanent) and of dynamic loads (transient);

higher number of contact points
- improve mechanical properties of soils (mainly friction angle φ), to satisfy construction requirements (sufficient stiffness of each layer, necessary for compaction of layers above) and to ensure stability of construction work in service;

- reduce the influence of water (lower porosity leads to lower permeability and increased resistance to erosion).

SOIL COMPACTION (different rules)

Description of phenomenon

Porosity reduction generated by compaction is due to:
↳ increasing density
- expulsion of air contained in soil volume,
↳ move the particles closer
- migration of water (minimal contribution since compaction is a quick phenomenon unlike consolidation: water contet does not change dramatically)
- compression of air which cannot be expelled (especially for clayey soils)

FACTORS WHICH INFLUENCE COMPACTION:

1. Soil type (A_i)
2. Water content (w) (easily controlled)
3. Compaction energy (E)
4. Compaction mode (static, dynamic way, with pressure ecc.)
5. Layer thickness and stiffness of support

energy will be distributed in different volumes

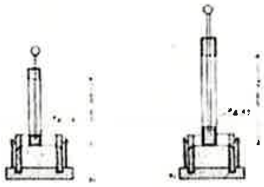
deformable support dissipate compaction energy (not very effective)

SOIL COMPACTION

Proctor test – experimental procedure

UNI EN 13286-2 (2005)

- Type A (AASHTO Standard – T 99)
- Type B (AASHTO Modificata – T 180)
  ↳ same principles but different "numbers"



	Standard	Modificato
numero di strati	3	5
massa del pestello	2,495 kg	4,535 kg
altezza di caduta	30,5 cm	45,7 cm
numero di colpi	25 - 56	25 - 56
energia per unità di volume [N/cm^2]	59	269

quite different

$$E = \frac{P_{maglio} \cdot h \cdot n_{\frac{c}{s}} \cdot n_s}{V_{fustella}}$$

Compaction energy per unit volume

SOIL COMPACTION

Proctor test – experimental procedure

↳ at least 5 determination with different water content

Amount of soil for 5 determinations:
- 15 kg for small mould
- 36 kg for large mould

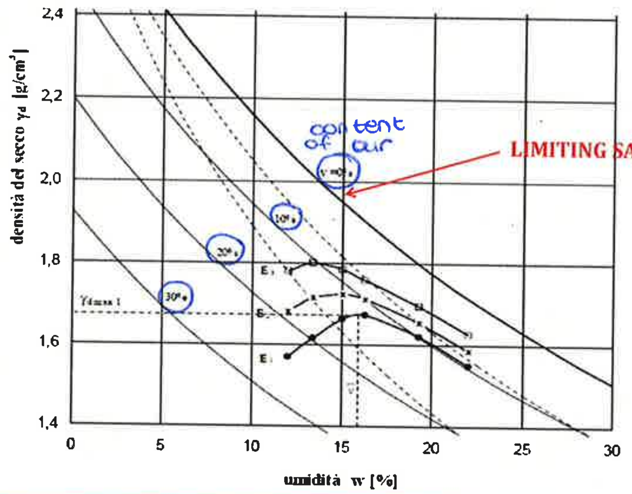
Procedure:
- drying at 50°C and disgregation;
- sieving at sieve 25 mm (if the retained is higher than 35 % of total mass the test cannot be performed);
- choice of small/large mould (small is the passing at 25 mm is entirely passing at 5 mm - n.4 ASTM);
- formation of single specimens (variable water contents).

09/10/2017

SOIL COMPACTION

REVIEW

Influence of compaction energy



LIMITING SATURATION CURVE

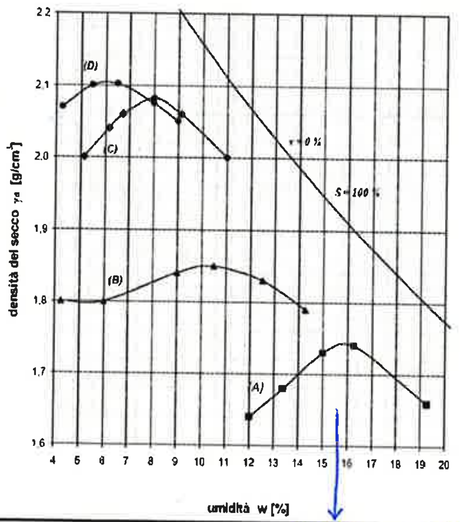
⇩

v = 0%

SOIL COMPACTION

↱ different curves for different type of soils

Influence of soil type - Examples (not assumed, useful not rules)



CURVE A

Fine-grained silty soil (A_4 or A_5) → the silt keep a lot of water
with quite high w_{opt} (w_{opt} = 15÷20%), with a significant survature of bell-shaped curve
↳ pointed curve

CURVE B (great for embankment)

Gravel sand ($A1_b$) generally higher than A and quite flat; optimum water content is approximately w_{opt} = 8÷12%; γ_s is close to γ_{smax} in a wide range of water contents
↳ much flatter curve

minimum variation from the optimum value leads to a significant decreas of dry density slope : pendenza

10/10/2017

- generic depth
- point with infinitesimal dimensions
- different stressed ↳ find principle directions
- as the veichle get closer, the effects increase (maximum is when it is exactly overhead the position of P)
- principale directions point the veichle so they rotate

SOIL MECHANICS

Mechanical behaviour of soils

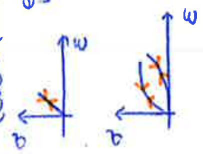
As a result of moving traffic the following occurs:

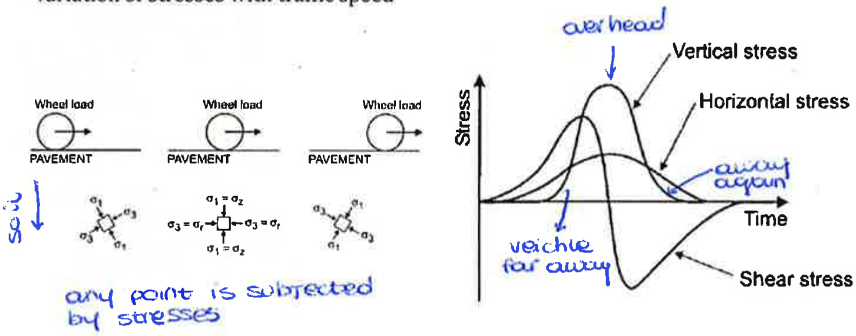
- rotation of principal planes (on which principal stresses arise) → not shear stress.
  directions
- variation of stresses as a function of time (shear increase, zero, decrease)
- dependency of elastic response from the state of stress → stiffness is related to the point
- variation of stresses with traffic speed

changing the stress stiffness changes (even for changing depth)

elastic material was a linear connection

non linear elastic material $\{ k = f(\varepsilon) \}$

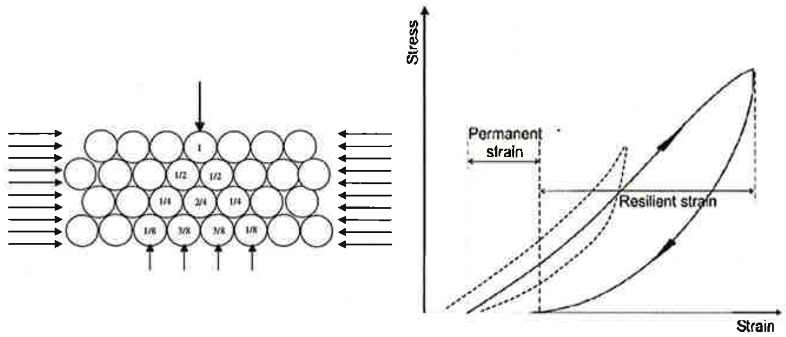




SOIL MECHANICS

Mechanical behaviour of soils

- not perfectly elastic
- strain response depends upon lateral confinement (= state of stress)
- stiffness depends upon stress state (non-linearity) and stress history



unloading isn't following the loading and in reloading the curve is different again.

10/10/2017

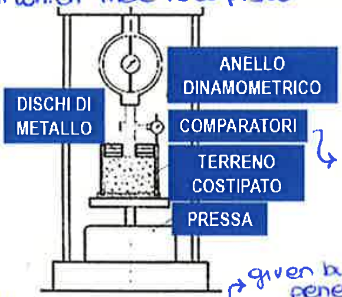
specific need: design thickness of pavement then test (CBR simulate the behaviour of soil)

CBR Method (*California Bearing Ratio*)

heavy disk with a hole in which there is a piston → it has a cross section smaller than the entire sample

TEST

1. Position mould in loading frame
2. Apply surcharge
3. Apply load with a speed of displacement equal to 1,27 mm/min
4. Reading of applied pressure corresponding to displacements of: 0.5, 1, 1.5, 2, 2.5, 3, 4, 5, 7 e 9 mm



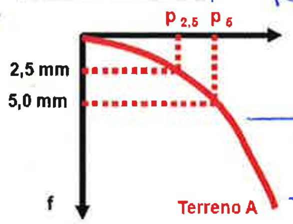
the press goes up and the soil compacts

$$CBR = \max \begin{pmatrix} 100 \dfrac{p_{2,5\,mm}}{p_{RIF-2,5\,mm}(70kg/cm^2)} \\ 100 \dfrac{p_{5\,mm}}{p_{RIF-5\,mm}(105kg/cm^2)} \end{pmatrix}$$

non dimensional value through these coefficients

given by a specific penetration

pression applied / area of cross section



theoretical curve with one curvature

digital equipment leads to a continuous curve (vs specific points)

⇩

EMPIRICAL APPROACH high value: very resistant soil (very stiff, in order to obtain this displacement we have to apply a huge strength)

⇒ unknown: real stress

⇒ it's linked both to stress and strain

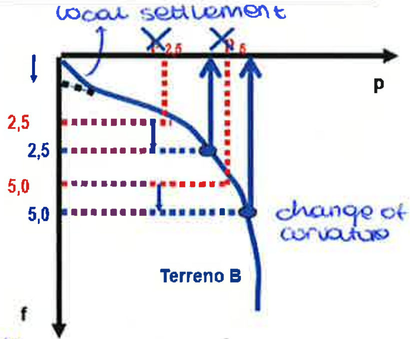
CBR Method (*California Bearing Ratio*)

it has to do with bearing capacity related to the stiffness

local settlement

CORRECTED CBR INDEX

Obtained by shifting the origin of pressure-displcament plot

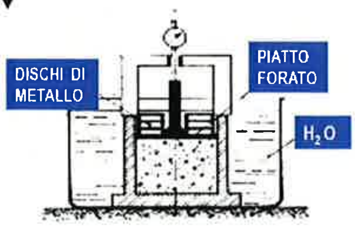


change of curvature

soil in the worst possible conditions

CBR INDEX AFTER SATURATION

Obtained by carrying out the test after 4 days of immersion in water



there can be an increasing of volume because of water

vertical piston → causes shear effects → DEVIATORIC STRESS
+ iso pressure condition → it can change volume → equal stress in all directions

RESILIENT MODULUS

Repeated loading triaxial tests (AASHTO T294)

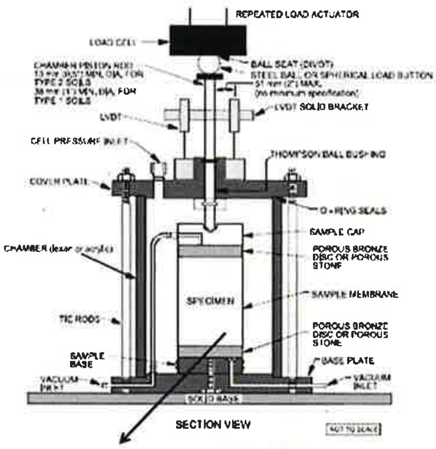
The test simulated the stress-strain state which results from vehicles

⇓

RATIONAL APPROACH

Two confinement conditions

- *Costant Cell Pressure* (CCP) (it could be pulsive or cycling)
- *Variable Cell Pressure* (VCP)



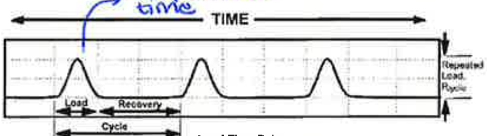
SLENDER SPECIMEN (H = 2D)
↳ 100 mm

reversible or elastic

RESILIENT MODULUS

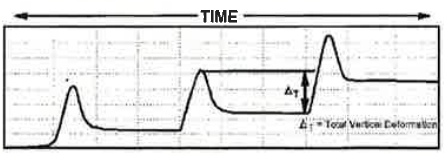
Repeated loading triaxial tests (AASHTO T294) → even other standards

very small time



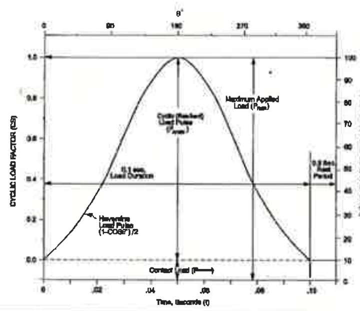
Load-Time Pulse

pulses which has this shape



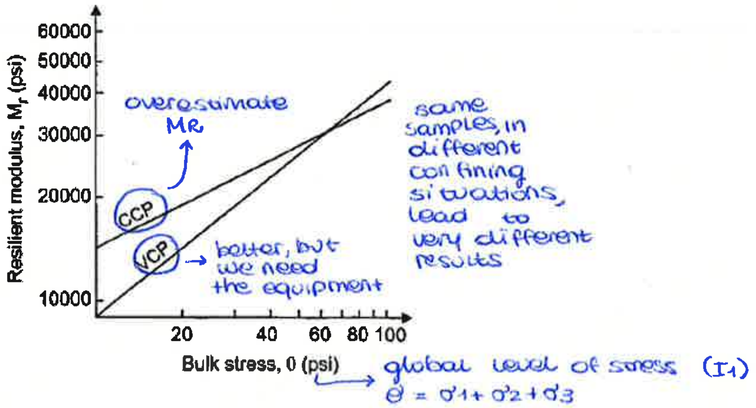
Deformation vs. Time

the permanent deformation increases but at some time it can be neglected



RESILIENT MODULUS

Repeated loading triaxial tests (AASHTO T294)



RESILIENT MODULUS

Repeated loading triaxial tests (AASHTO T294)

PERMANENT DEFORMATION

Evaluation of behaviour with respect to rutting → $\varepsilon_P = \varepsilon_a A \cdot N^{-B}$

⇩

SOTTOFONDO

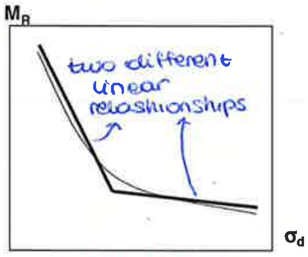
RESILIENT MODULUS

Models surface prevalent interaction
different character → shear effect
Fine cohesive materials

Thompson – Elliott

$$M_R = k_1 + k_3 (k_2 - \sigma_d) \quad \text{con } \sigma_d < k_2$$
$$= k_1 + k_4 (k_2 - \sigma_d) \quad \text{con } \sigma_d > k_2$$

it controls the level of stiffness they are very sensitive to shear



"Stress – softening"

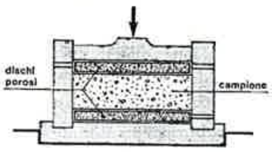
COMPRESSIBILITY

Edometric tests typical for a load applied in long area

- Totally saturated conditions
- Partially saturated conditions

1. Axial lod applied to specimen;
2. Settlement; (in time) → only vertical
3. Measurement of displacements.

Pressure increase: $p_0 \rightarrow p_0 + \Delta p$



$e_0 \rightarrow e$

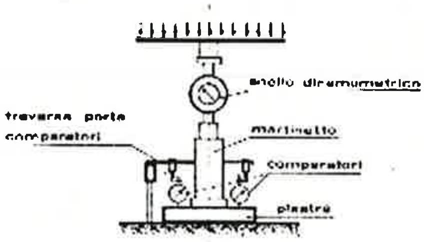
change of porosity

$$\boxed{a_v = \frac{e_0 - e}{\Delta p}}$$

COMPRESSIBILITY COEFFICIENT

BEARING ~~BERING~~ CAPACITY

Plate loading test → apply load → measuring displacements



EQUIPMENT

Circular metal plate → loaded by an adequate sistem

Hydraulic actuator

Transducers (usually 3)

↳ set a triangle on 120° from the centre (equally space)

BEARING CAPACITY

Plate loading test

TEST

1. Levelling of surface and plate positioning
2. Set up of actuator and counterweight (e.g. rear axle of heavy vehicle)
3. Set-up of transducers arranged at 120° with arms fixed to supporting beam (supports resting at at least 1 m from plate)
   ↳ undeformable support (suspending)
4. Imposition of given load/pressure values and reading of corresponding displacements (stabilization of readings: diffrence smaller than 0.02 mm after 1 minute) → time depending features (initial settlement and then displacement)

GERMAN STANDARD (DIN): specific frequency of reading (1/2 minutes)
↳ no time for stabilization

BEARING CAPACITY

REVIEW

Behaviour of soil under loading can be described by referring to two main models

BOUSSINESQ

→ Soil is considered as a elastic, homogeneous and isotropic half-space

$$p = \frac{E}{1-\nu^2} \cdot \frac{2\delta}{\pi \cdot r}$$

In the original theory $\frac{2}{\pi} = \frac{1}{2}$ because the plate isn't completely crashproof

→ average pressure
→ two unknowns (E and ν) → fixed $\nu = 0{,}30$

WINKLER

→ Soil is considered as a bed of independent elastic springs

→ unconnected
→ no shear tranfer in the individual elements which compose soil

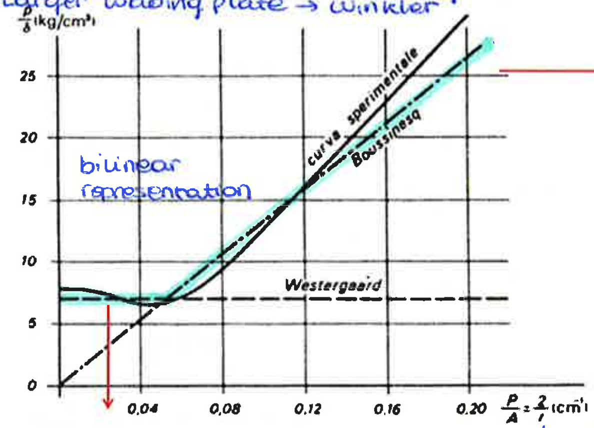
$$p = k \cdot \delta$$

BEARING CAPACITY

REVIEW

Model compared to experimental evidence (⇒ experimental curve)

Small loading plate → Boussinesq
Larger loading plate → Winkler



Small plates: "Boussinesq" behaviour
$\frac{p}{\delta}$ changes with $\frac{1}{r}$

relationship between perimeter and cross section (2/r)

Large plates: "Winkler" behaviour
$\frac{p}{\delta} = \text{cost}$

BEARING CAPACITY

Standard CNR n. 146/1992

$$M_d = \frac{\Delta p}{\Delta \delta} \cdot D$$

$\boxed{\text{Test with plate D = 30 cm}}$

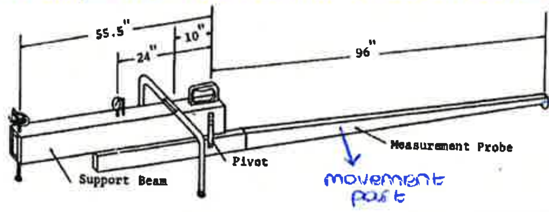
Deformation modulus
(instead of elastic modulus)

⇒ **Control**

(applicable to all parts of earthworks)

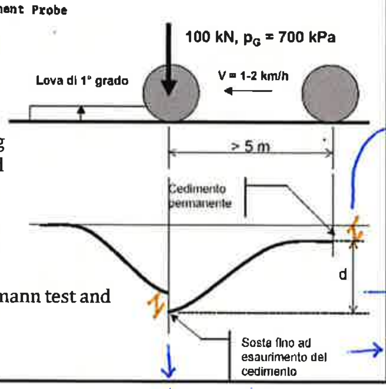
BEARING CAPACITY
(other methods)

Benkelmann beam (CNR n. 141/1992)
↳ simple but not modern or sofisticated



Measurements are performed by considering the displacement of a point under to the action of a moving vehicle of known characteristics (which gets closer and then leaves).

Total displacment = d (recovered) + p (permanent)



residual deformation which depends on the cicle of loading and reloading

how displacements change in time

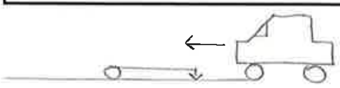
elastic recovery

stabilize the load

$$M_d = \frac{84}{d}$$

M_d: kg/cm²; d: cm

Empirical correlation between Benkelmann test and plate loading test



the vehicle is standing sideways of the probe. SONDAGGIO

10/10/2017

BEARING CAPACITY

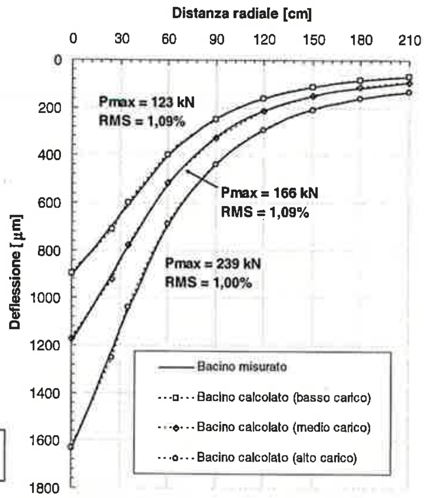
Falling Weight Deflectometer (FWD)

Mechanical characteristics of subgrade (**Es**) or pavement (**Ei**) are derived from the deflection basin provided that the cress-section is known (**Back-calculation procedure**)

Comparison between measured and calculated basin:

$$RMS(\%) = 100 \cdot \sqrt{\frac{1}{9}\sum_{i=1}^{9}\left(\frac{d_{ci}-d_{mi}}{d_{mi}}\right)^2}$$

TREATED IN DETAIL IN THE PART ON PAVEMENTS (STRUCTURAL EVALUATION)



BEARING CAPACITY

Light Weight Drop Tester (LWDT) (mini version of FWD)

⇒ Tipically in Germany

↑ a system of springs (rebounded wood)

the mass is pulled in hight and then released to measure the displacements

↳ 30 cm plate

Very useful equipment, easy to handle an to use, for the quick control ofearthworks (embankments, subgrades, foundations)

⇒ Just for soils not for finished pavements

vertical or dinamic modulus

$$E_{s,din} = \frac{22{,}5}{d} \quad \left(\frac{N}{mm^2} = MPa\right)$$

d cm

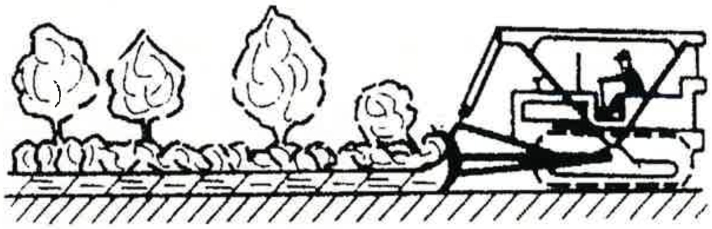
From Boussinesq with $d = 30$ cm

⇒ greater number of tests

Construction of the road prism

CLEARING AND GRUBBING

Removal of trees, bushes, roots.
Removed material is detained by the Contractor which handles it disposal.



Construction of the road prism

REMOVAL OF TOPSOIL

Topsoil = organic. (it's compressible, its presence is negative!)
Total removal to prevent contamination of other excavated material.
Reuse for slope protection.

↳ clean soil

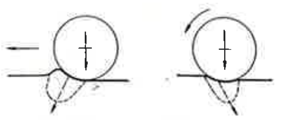
Construction of the road prism

EMBANKMENT FOUNDATION

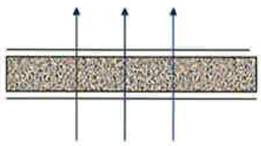
Functions/requisites → level → compact → protect

- construction evenness
- resistance to embankment geostatic stresses;
  ⇒ compaction activities
- embankment protection (capillarity and contamination)

Compaction



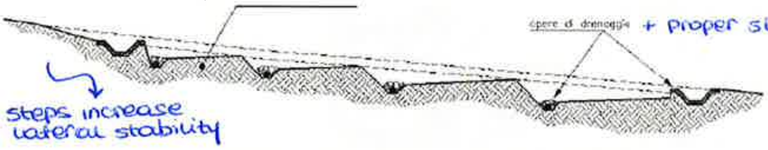
Anti-capillary materials



Construction of the road prism

EMBANKMENT FOUNDATION – ***Transverse steps***

piano di posa non idoneo e sostituzione con materiale adatto;
formazione gradoni



piano di posa idoneo e formazione gradoni

Construction of the road prism

COMPRESSIBLE SOILS – *Improvement techniques*

The purpose of improvement techniques is to **accelerate consolidation phenomena**

COMPRESSIBLE SOILS (we may have too high settlements)
↳ accelerate consolidation so make soil better

- Compressible silts ⟹ IMPROVEMENT TECHNIQUES
- Non-organic clays
- (Organic soils)

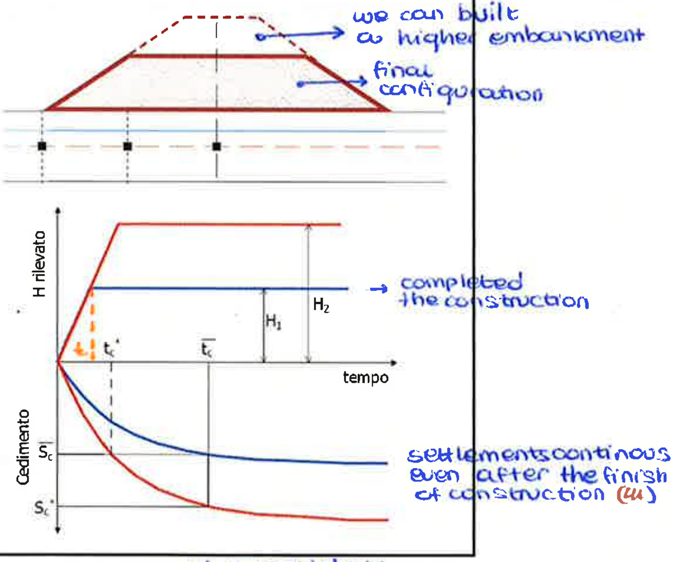
- **Preloading**
- **Vertical drains**
- **Column treatment**
- **Void consolidation**

Construction of the road prism

COMPRESSIBLE SOILS – *Preloading*

$\overline{t_c}$ = consolidation time

$\boxed{S_c^* > \overline{S_c}}$ $\boxed{\overline{S_c}(H_2) \rightarrow t_c^* < \overline{t_c}}$

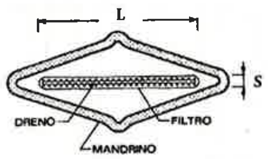


the end of consolidation is shorter ⇒ after that we can remove extra "embankment"

Construction of the road prism

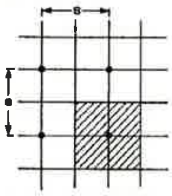
COMPRESSIBLE SOILS – *Precast drains*

Characterized by
- lower cost
- ease/speed of installment



Triangular mesh

Square mesh



Dreno	Dimensioni		Materiali		k	d_w
	L [mm]	S [mm]	Anima	Filtro	[m/s]	[mm]
Kjellman	100	3.5	Cartone	Cartone	$1{\cdot}10^{-7}$	66
Mebra	95	3.2	Polietilene	Carta trattata	$6{\cdot}10^{-9}$	63
Geodrain	95	4.0	Polietilene	Carta trattata	$6{\cdot}10^{-9}$	63
Colbond	300	4.0	Poliestere non tessuto	Poliestere non tessuto	$3{\cdot}10^{-4}$	194
Alidrain	100	7.0	Plastica	Cellulosa	$3{\cdot}10^{-6}$	68
Castle Drain Boards	94	2.6	Poliolefine	Tessuto non tessuto	$2{\cdot}10^{-4}$	62

Construction of the road prism

COMPRESSIBLE SOILS – *Column treatment*

- JET-GROUTING
- VIBROSUBSTITUTION
- VIBROCOMPACTION
- DEEP-MIXING
- COMPACTION GROUTING

2. Near the construction area, three different soil are available. Knowing their characteristics (**Table 3** and **4**), identify the optimum soil to employed in the realization of the embankment (using both the Highway Research Board and European approach).

Diameter [mm]	Retained [g]		
	A	B	C
63	-	-	-
31,5	165,2	3567,1	-
16	516,7	6752,9	370,6
8	521,0	4736,8	488,3
4	578,6	2973,8	850,5
2	269,2	2073,4	1647,1
1	1536,0	1101,4	2055,6
0,5	990,8	1195,7	844,1
0,4	545,5	412,1	1008,9
0,250	899,0	832,1	3808,9
0,125	875,9	796,8	2964,8
0,075	847,7	503,1	2594,2
0,063	204,1	404,3	888,6
0,002	4706,8	925,8	523,7
< 0,002	1400,0	955,4	256,8
Total	14056,5	27230,7	18302,1

Table 3: Sieve analysis results

	A	B	C
w_L [%]	42,2	10,5	-
w_P [%]	34,9	5,8	NP

Table 4: Atterberg's limit

Classification of the support soil

1

Classification chart (HRB approach)

- $P_{2\,mm}$;
- $P_{0{,}425\,mm}$;
- $P_{0{,}075\,mm}$;
- w_L;
- PI;
- GI.

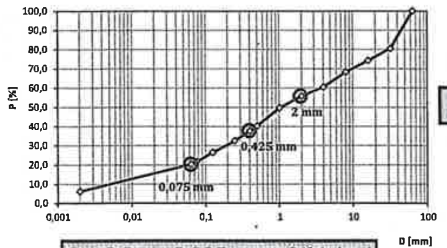
HRB-CLASSIFICATION OF SOILS AND SOIL-AGGREGATE MIXTURES

General Description	Granular materials (35% or less passing 75 micron IS sieve)							Silt clay materials (more than 35% passing 75 micron IS sieve)			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5 A-7-6
Sieve analysis, percent passing											
2.0 mm IS sieve	50 max										
425 micron sieve	30 max	50 max	51 min								
75 micron sieve	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing 425 micron sieve											
Liquid Limit				40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plasticity Index	6 max		NP	10 max	10 max	11 min	11 max	10 max	10 max	11 min	11 min
Group Index			Zero			4 max		8 max	12 max	16 max	20 max
Usual type of significant constituent materials	Stone fragments gravel and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General rating as subgrade	Excellent to good					Fair to poor					

3

Classification of the support soil

Classification chart (HRB approach)



$PI = w_L - w_P$

$GI = 0.2 \cdot a + 0.005 \cdot a \cdot c + 0.01 \cdot b \cdot d$

- $a = P_{0{,}075} - 35$ (0-40)
- $b = P_{0{,}075} - 15$ (0-40)
- $c = w_L - 40$ (0-20)
- $d = PI - 20$ (0-20)

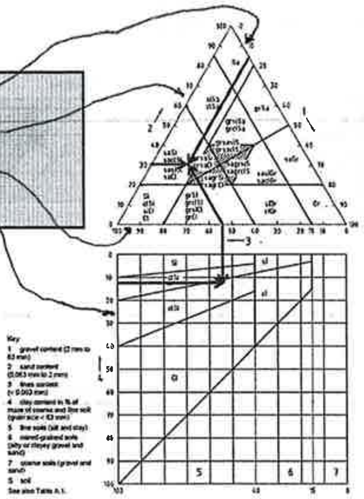
4

Classification of the support soil

2

EN 14688 – 2 classification

- Gravel content (2 – 63 mm);
- Sand content (0,063 – 2 mm);
- Fines content (< 0,063 mm);
- Clay content (< 0,002 mm).



7

Embankment soil selection

Three possible candidate:

Soil A

Size [mm]	Retained [g]
63	-
31,5	165,2
16	516,7
8	521,0
4	578,6
2	269,2
1	1536,0
0,5	990,8
0,4	545,5
0,25	899,0
0,125	875,9
0,075	847,7
0,063	204,1
0,002	4706,8
< 0,002	1400,0

w_L [%]	42,2
w_P [%]	34,9

Soil B

Size [mm]	Retained [g]
63	-
31,5	3567,1
16	6752,9
8	4736,8
4	2973,8
2	2073,4
1	1101,4
0,5	1195,7
0,4	412,1
0,25	832,1
0,125	796,8
0,075	503,1
0,063	404,3
0,002	925,8
< 0,002	955,4

w_L [%]	10,5
w_P [%]	5,8

Soil C

Size [mm]	Retained [g]
63	-
31,5	-
16	370,6
8	488,3
4	850,5
2	1647,1
1	2055,3
0,5	844,1
0,4	1008,9
0,25	3808,9
0,125	2964,8
0,075	2594,2
0,063	888,6
0,002	523,7
< 0,002	256,8

w_L [%]	18,8
w_P [%]	10,3

8

SOIL A $w_L[\%] = 42,2$ $w_P[\%] = 34,9$

SIZE	Retained [g]	R_c [g]	R_c [%]	P_c [%]
63	-	-	0	100
31,5	165,2	165,2	1,175	98,83
16	516,7	681,9	4,85	95,15
8	521	1202,9	8,56	91,44
4	578,6	1781,5	12,67	87,33
2	269,2	2050,7	14,59	85,41
1	1536,0	3586,7	25,51	74,49
0,5	990,8	4577,5	32,56	67,44
0,4	545,5	5123,0	36,44	63,56
0,25	899,0	6021,9	42,84	57,16
0,125	875,9	6897,8	49,07	50,93
0,075	847,7	7745,5	55,10	44,9
0,063	204,1	7949,6	56,55	43,45
0,002	4706,8	12656,4	90,04	9,96
<0,002	1400	14056,4	100	0

$\boxed{TOT = 14056,4}$

$PI = w_L - w_P = 7,3\%$

① classification chart (HRB)

$P_2 = 85,41\%$

$P_{0,425} = 63,56\%$

$P_{0,075} = 44,9\%$

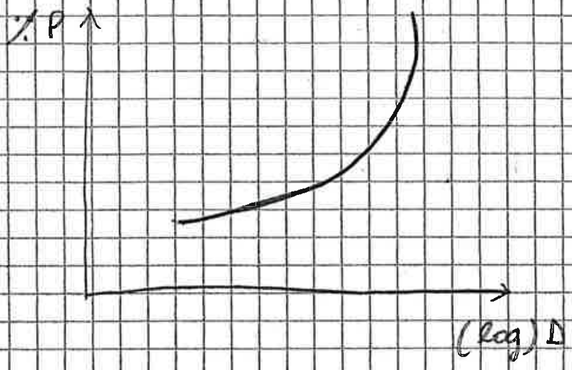
$w_L = 42,2\%$

$PI = 7,3\%$

$\boxed{A-5}$

$GI = 0,2 \cdot a + 0,005 \cdot a \cdot c + \cancel{0,01 \cdot b \cdot d} = 3,07$

$a = 9,9$
$b = 29,9$
$c = 2,2$
$d = 0$



$w_L = 41{,}2\ \%$

$w_P = 32{,}2\ \%$

$PI = w_L - w_P = 9\%$

GI

- N. 10 ≈ 2 mm   > 2 GRAVEL
  < 2 SAND
- N. 40 = 0,425 mm   COARSE SAND / FINE SAND
- N. 200 = 0,075 mm   COHESIVE SOIL / NOT COHESIVE SOIL
- w_L
- PI
- $GI = 0{,}2 \cdot a + 0{,}005\, a \cdot c + 0{,}01 \cdot b \cdot d$

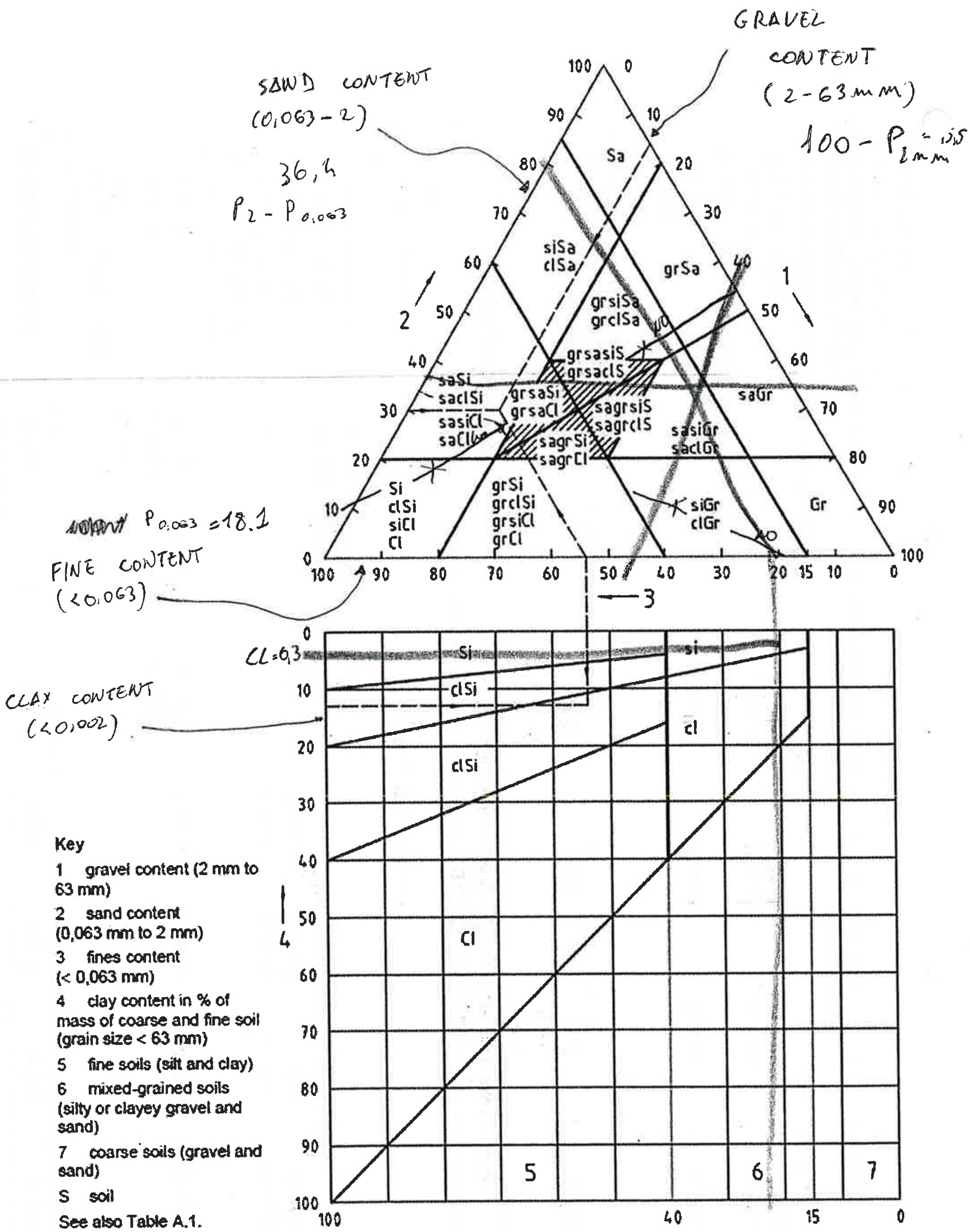
- $P_{2\,mm} = 56{,}5\ \%$
- $P_{0{,}425} = 35{,}9\%$
- $P_{0{,}075} = 19{,}5\ \%$
- $w_L = 41{,}2\%$
- $PI = 9\%$

Table $\boxed{A\text{-}2\text{-}5}$

- $GI = 0{,}2 \cdot a + 0{,}005 \cdot a \cdot c + 0{,}01 \cdot b \cdot d = 0$

$\boxed{0 < \ < 20}$ every can be only between 0 and 20

- $a = P_{0{,}075} - 35\ (0-40) = 19{,}5 - 35 = 0$
- $b = P_{0{,}075} - 15\ (0-40) = 4{,}5$
- $c = w_L - 40\ (0-20) = 1{,}2$
- $d = PI - 20\ (0-20) = 0$



Key

1 gravel content (2 mm to 63 mm)

2 sand content (0,063 mm to 2 mm)

3 fines content (< 0,063 mm)

4 clay content in % of mass of coarse and fine soil (grain size < 63 mm)

5 fine soils (silt and clay)

6 mixed-grained soils (silty or clayey gravel and sand)

7 coarse soils (gravel and sand)

S soil

See also Table A.1.

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Non sono da ricordare

$$S_i = \frac{\gamma \cdot h}{E_u} \cdot \frac{a^2}{a - a'} \cdot \left\{ r_H - \left(\frac{a'}{a} \right)^2 \cdot r'_H \right\}$$

$$S_c(t) = H \cdot \frac{C_c}{1+e_0} \cdot \log \frac{\sigma'_{v0} + \Delta\sigma'_v}{\sigma'_{v0}}$$

$$\sigma_z = \frac{q}{\pi} \cdot [\alpha + \sin(\alpha) \cdot \cos(\alpha + 2\beta)]$$

$$\sigma_z = \frac{q}{\pi} \cdot \left[\frac{x}{B} \cdot \alpha - \frac{1}{2} \cdot \sin(2\beta) \right]$$

GSC	E_u/c_u		
	PI < 30	30 < PI < 50	PI > 50
< 3	600	300	125
3 - 5	400	200	75
> 5	150	75	50

$$C_c = 0{,}009 \cdot (w_L - 10)$$

$$T_v = \frac{c_v \cdot t}{H_{dr}^2}$$

$$U_m = \frac{\left(4 \cdot \frac{T_v}{\pi}\right)^{\frac{1}{2}}}{\left[1 + \left(4 \cdot \frac{T_v}{\pi}\right)^{2,8}\right]^{0,179}}$$

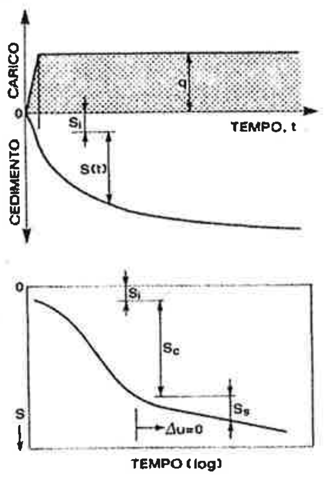
Settlements

Any Technical Specifications requires that if the predicted settlement of the support soil of the embankment will exceed a certain amount (normally 15 cm), a detailed study on their control and monitoring should be provided by the Contractor.

The construction of the embankment must be planned to obtained a residual settlement at the end of its construction less than the 10% of the total settlement expected (in any case less than 5 cm).

3

Settlements



$$\boxed{S = S_i + S_c(t) + S_s(t)}$$

Assessment of:

- Immediate settlement S_i;
- Consolidation settlement $S_c(t)$;
- Secondary settlement $S_s(t)$.

4

Settlements

IMMEDIATE SETTLEMENT

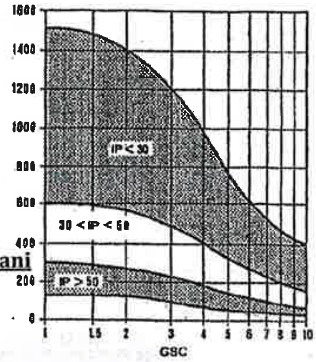
E_u : undrained Young modulus

$$\boxed{E_{u,m} = \frac{D_m \cdot H}{\sum_{i=1}^{n} \frac{D_i \cdot H_i}{E_{u,i}}}}$$

Magnan (layered soils) → not homogeneous

GSC	E_u/c_u		
	PI < 30	30 < PI < 50	PI > 50
< 3	600	300	125
3 - 5	400	200	75
> 5	150	75	50

Duncan and Buchignani (homogeneous soils)



Settlements

IMMEDIATE SETTLEMENT

$$\boxed{S_i = \frac{\gamma \cdot h}{E_u} \cdot \frac{a^2}{a - a'} \cdot \left\{ r_H - \left(\frac{a'}{a}\right)^2 \cdot r'_H \right\}}$$

GIROUD APPROACH

- a: semi-width of the bottom base = 16,75 m;
- a': semi-width of the upper base = 11,5 m;
- γ: density of embankment soil;
- h: embankment height = 3,5 m;
- E_u: undrained Young modulus;
- r_H e r'_H: Giroud parameter.

8

Settlements

IMMEDIATE SETTLEMENT: evaluation of r_h and r'_h

For each point (P, Q and R) we should know **x** (reference abscissa), geometry of embankment (**a** and **a'**) and the thickness of the soft soil (**H**) to use the Giroud chart and evaluate r_H and r'_H:

Point	x	a	a'	H	x/a	x/a'	H/a	H/a'	r_h	r'_h
P										
Q										
R										

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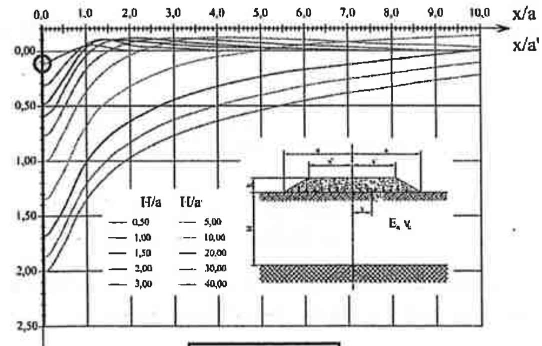
Settlements

IMMEDIATE SETTLEMENT: evaluation of r_h and r'_h

Point P:
- x/a' = 0
- H/a' ≈ 0,4



$r'_H = 0,139$

N.B.: always approximate to the next value

Settlements

IMMEDIATE SETTLEMENT: determination of the density γ

We are still in the design phase (nothing has yet been built) → we should hypothesize a reliable value of γ:

Example of Italian Technical Specifications

Tabella 1.11 Criteri di qualità e requisiti per gli strati di rilevato e di sottofondo

STRATO	Tipo di Strada (3)	Grado d'addensamento % $\gamma_{s\,max}$ di laboratorio	Modulo di deformazione Md [N/mm²]	Δh (4) [mm]
Sottofondo (1)	Autostrade ed Extraubane principali	≥ 95 % AASHO Mod	≥ 50	< 2,5
	Altre	≥ 100 % AASHO St.	≥ 40	< 3,0
Rilevato (2)	Autostrade ed Extraubane principali	≥ 92 % AASHO Mod	≥ 30	< 4,0
	Altre	≥ 97 % AASHO St.	≥ 25	< 5,0

→ $\boxed{\gamma = 95\%\,\gamma_{u,max}}$

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Settlements

IMMEDIATE SETTLEMENT

We can solve the Giroud equation and calculate the immediate settlement for each of the investigated point (P, Q and R).

The layer settlement will be the mean value of the abovementioned settlements:

$$S_I = \frac{S_{I,P} + S_{I,Q} + S_{I,R}}{3}$$

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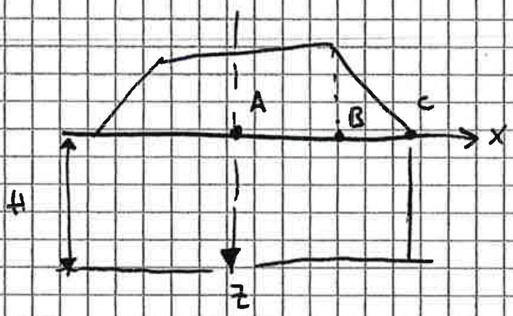
$a' = \frac{23}{2} = 11,5$

Given graph. $\frac{x}{a}$ or $\frac{x}{a'}$ ↓ r_h, r'_h $\frac{H}{a}$ or $\frac{H}{a'}$



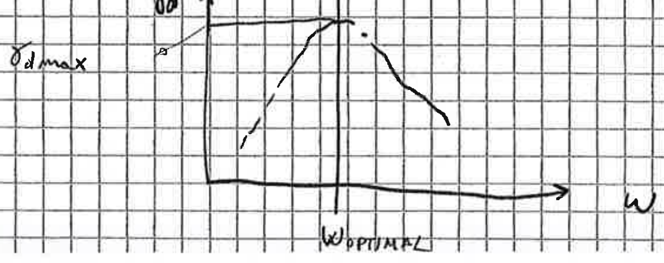
Evaluating point.

- for I use: r_H → x/a, H/a ; r'_H → x/a', H/a'

	x	x/a	x/a'	H/a	H/a'	r_h	r'_h
A	0	0	0	0,3 ↓ 0,5	0,43 ↳ 0,5	0,123	0,123
B	11,5	0,69	1	0,3 ↳ 0,5	0,4 ↳ 0,5	0	-0,044
C	16,75	1	1,45	0,5	0,5	-0,046	-0,02

- $h = 3,5\ m$

- for the γ: (Proctor)



$$\gamma_w = \gamma_d (1+w) \Rightarrow \gamma_w = 1,977\ g/cm^3$$

$$S_i = \frac{\gamma \cdot B}{E_u} \frac{a^2}{a-a'} \left\{ r_H - \left(\frac{a'}{a}\right)^2 \cdot r'_h \right\}$$

$g/cm^3 \Rightarrow KN/m^3$ $\qquad E_U\ [KN/m^2]$

$\gamma_w = 19,388\ KN/m^3$

$$\left[\frac{KN}{m^2}\ m\ \frac{m^2}{KN} \cdot m^2 \cdot \frac{m^2}{m}\ \frac{m^2}{m^2}\right] = m$$

(A) $$\frac{19,388 \cdot 3,5}{204\,000} \left(\frac{16,75^2}{16,75-11,5}\right) \left\{ 0,123 - \left(\frac{11,5}{16,75}\right)^2 \cdot 0,123 \right\} =$$

$= 1,2$ cm

(B) $= 0,4$ cm

(C) $= -0,5$ cm   we are in undrain condition

$$\Rightarrow S_i = \frac{1,2+0,4-0,5}{3} = 0,4\ cm$$

2 TERZAGHI FORMULA

Terzaghi and peak

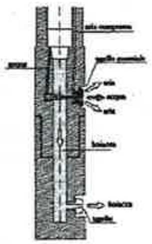
$$S_c(t) = H \cdot \frac{C_c}{1+e_0} \log \frac{\sigma'_{v0} + \Delta\sigma'_v}{\sigma'_{v0}}$$

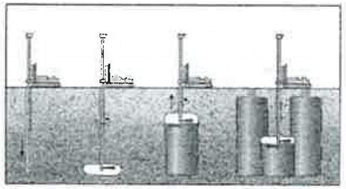
Construction of the road prism

COMPRESSIBLE SOILS – ***Column treatment***

JET-GROUTING

Sistema	Fluido	Pressione [MPa]	Velocità getto [m/s]	D [m]
Monofluido	Boiacca di cemento	20 ÷ 40	100 ÷ 250	0.40 ÷ 0.60
Bifluido (jumbo special pile)	Boiacca di cemento Aria	25 ÷ 40 0.7 ÷ 1	100 ÷ 200 > 330	0.80 ÷ 1.60
Trifluido (Kaijma)	Boiacca di cemento Aria Acqua	2 ÷ 6 0.7 ÷ 1.7 40 ÷ 60	50 ÷ 80 > 330 350 ÷ 500	0.80 ÷ 2.50

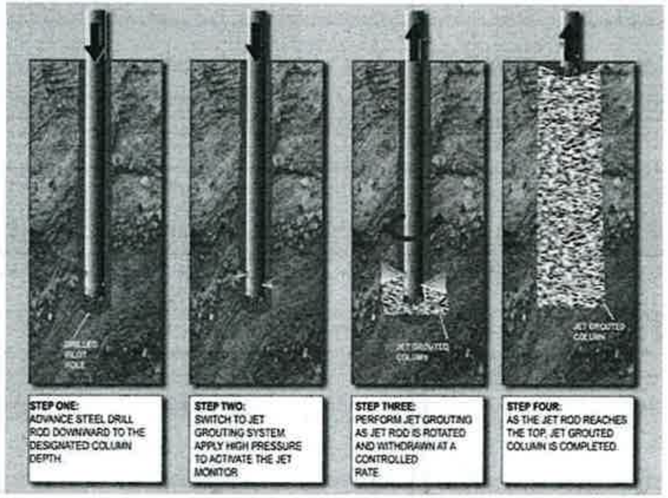




Construction of the road prism

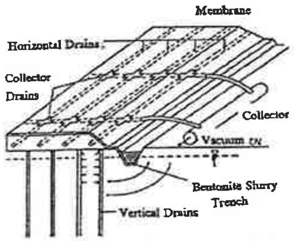
COMPRESSIBLE SOILS – ***Column treatment***

JET-GROUTING

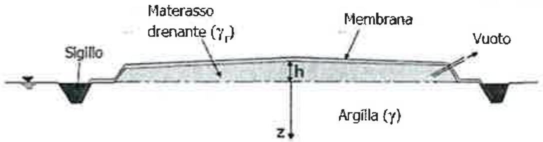


Construction of the road prism

COMPRESSIBLE SOILS – ***Vacuum consolidation***



Soil is covered by an air-tight membrane to which vacuum is applied



NO VACUUM

$\sigma_v = \gamma \cdot z + \gamma_r \cdot h$

$u = \gamma_w \cdot z$

$\sigma'_v = \gamma \cdot z + \gamma_r \cdot h - \gamma_w \cdot z = \gamma' \cdot z + \gamma_r \cdot h$

WITH VACUUM

$\sigma_v = \gamma \cdot z + \gamma_r \cdot h$

$u = \gamma_w \cdot z - P_a$

$\sigma'_v = \gamma \cdot z + \gamma_r \cdot h - (\gamma_w \cdot z - P_a) = \gamma' \cdot z + \gamma_r \cdot h + P_a$

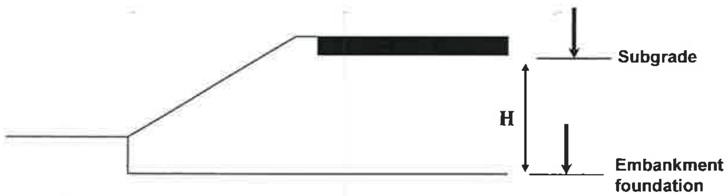
Construction of the road prism

EMBANKMENT FOUNDATION – ***Bearing capacity requirements***

Deformation modulus M_d (first loading cycle) comprised in the range 0,05÷0,15 N/mm²:

- 15 N/mm², for H > 2,00 m;
- 20 N/mm², for 1,00 < H < 2,00 m;
- 30 N/mm², for 0.50 < H < 1,00 m.

(CIRS Technical Specifications)



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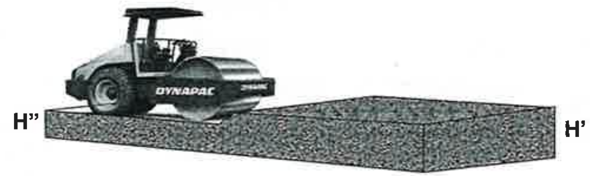
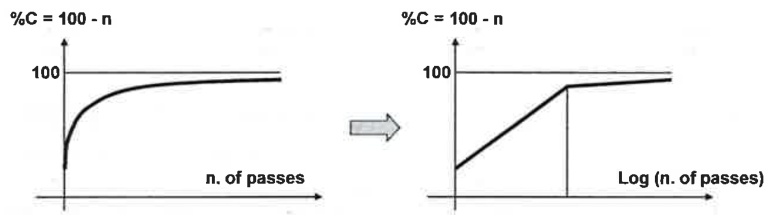
GENERAL PRINCIPLES OF IN SITU COMPACTION





Construction of the road prism

GENERAL PRINCIPLES OF IN SITU COMPACTION

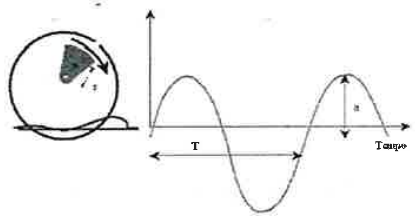
Static compaction
Based on the action of dead weight of equipment which translates into vertical stresses. Internal friction is overcome and soil volume is reduced.

Limited effect in depth (effects typically extend down to 20 cm).
Smooth static compaction is useful for finishing operations after oscillatory/vibratory compaction (limits the risks of suface disgregation).

Construction of the road prism

GENERAL PRINCIPLES OF IN SITU COMPACTION

Dynamic compaction
Based on the transmission of vibrations to soil (with superpose with dead-weight effects). Dynamic forces rearrange soil particles by reducing internal friction.



Vibration is induced by an eccentric mass which rotates around the drum axis.

Construction of the road prism

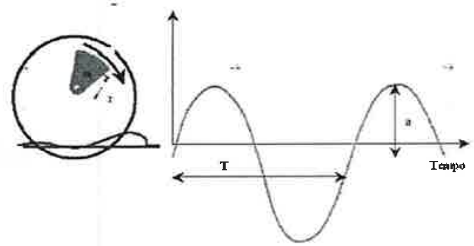
DYNAMIC COMPACTION

m_e = eccentric mass

r = eccentricity

f = oscillation frequency (Hz)

ω = pulsation (rad/s)



$$v = 2\pi \cdot f \cdot r = \omega \cdot r$$

$$a_c = \frac{v^2}{r}$$

$$F_c = m_e \frac{v^2}{r} = M_e \cdot \omega^2$$

$\longrightarrow M_e = m_e \cdot r$ ***(Eccentricity moment)***

$\longrightarrow$ ***Centrifugal force transmitted to drum***

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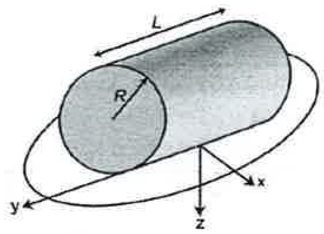
DYNAMIC COMPACTION

Lundberg model

Rigid body on elastic homogeneous and isotropic support



$$z_d = \frac{2\cdot(1-\upsilon^2)}{\pi\cdot E}\cdot\frac{F_s}{L}\cdot\left(1{,}8864+\ln\frac{L}{b}\right)$$

$$b = \sqrt{\frac{16\cdot R\cdot(1-\upsilon^2)}{\pi\cdot E\cdot L}\cdot F_s}$$ *Contact width of body (drum)*

↓

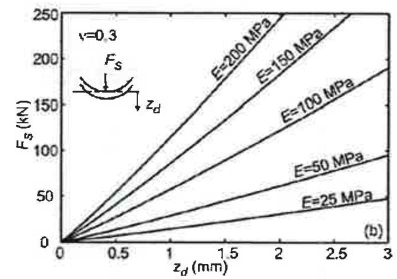
Parameter used for the control of compaction characteristics

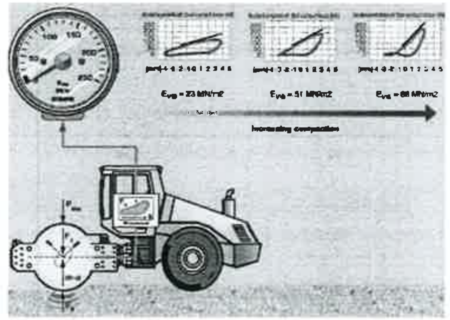
Construction of the road prism

INTELLIGENT COMPACTION

Several compactors have a measurement system which allows real-time monitoring of mechancial properties of soil and the consequent modification of the compaction procedure in order to obtain required final results ***(Intelligent Soil Compaction)***

F_s and z_d measured by equipment

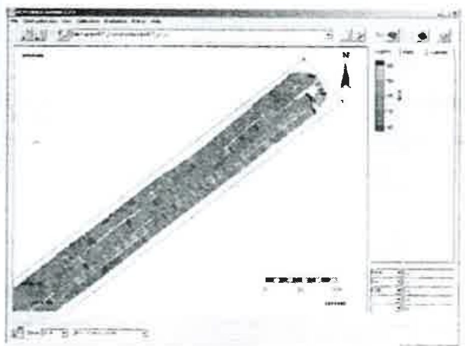




Estimate of E (E_{VIB})

Construction of the road prism

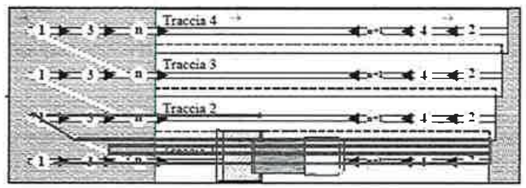
INTELLIGENT COMPACTION



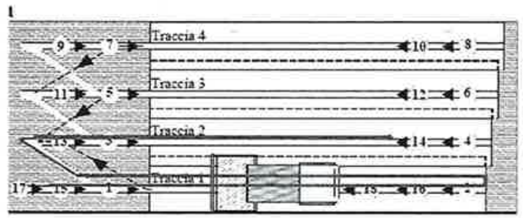
Construction of the road prism

COMPACTION TECHNIQUES

"STRIP by STRIP"



"SUPERPOSED CHANGE"



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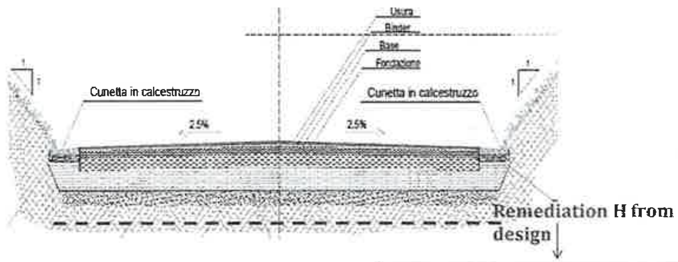
Construction of the road prism

SUBGRADE

Soil volume in which the effects of traffic loading are non-negligible; it is the zone of transition between embankment/ground and pavement.



- **Substitution of in situ material**
- **Stabilization of in situ material**

Construction of the road prism

EMBANKMENTS AND SUBGRADES – *Requirements*

IN SITU DENSITY

Subgrade* → $\gamma_{s,\,situ} \geq 95\%$ AASHTO Mod.

Embankment → $\gamma_{s,\,situ} \geq 92\%$ AASHTO Mod.

BEARING CAPACITY

Subgrade* → $M_d \geq 50$ N/mm^2

Embankment → $M_d \geq 30$ N/mm^2

⇨ To control in the range $w_{opt} - 2\% < w < w_{opt} + 2\%$

*** Typical minimum values; can be different depending upon pavement design assumptions**

Construction of the road prism

SUBGRADE – *Employed soils*

Evenness of pavement laying surface leads to exclusion of particles greater than D=100 mm;
Use of granular soils, well-distributed, preferably composed of crushed particles, with low fine content (percent passing the 0,075 mm sieve lower than 12%) and not plastic (PI<6).
Materials belonging to groups A1-a are of premium quality.
Alternative materials:
- Soils of groups A1-b;
- Soils of groups A2-4 ed A2-5, with percent passing the 0.075 mm sieve greater than 12%, preliminarily subjected to stabilization with cement or cement-lime;
- Soils of groups A2-6 ed A2-7 with a percentage of fines greater than 5% preliminarily subjected to stabilization with lime or cement-lime;
- Silts of groups A4 ed A5 if subjected to cement-lime stabilization, and clays of groups A6 ed A7, with limited plasticity (PI < 25%), if subjected to lime stabilization.

Construction of the road prism

EMBANKMENT AND CUT SECTIONS – *Slopes*

Protectioni of slopes with organic soil of approximately 30 cm thickness; progressively laid in horizontal strips and compacted. Seeding should be performed in due time with proper selected seeds (as a function of local conditions and construction season). Seeding may be repeated to obtain desired protection and aesthetics.

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EARTHWORKS

TRANSFORMATION COEFFICIENTS

In order to identify the equipment to employ for earthworks, it is necessary to know the ratio between the various volumes, defined by means of **transformation coefficients.**

γ_b, γ_s and γ_c : densities corresponding to bank, loose and compacted conditions

The following relationships hold (for a given, constant mass **P** of soil):

SWELL FACTOR → f_r (from bank to loose) [%] :

$$f_r = \left(\frac{V_s - V_b}{V_b}\right) \cdot 100 \quad = \left(\frac{V_s}{V_b} - 1\right) \quad = \left(\frac{\gamma_b}{\gamma_s} - 1\right) \cdot 100$$

LOADING FACTOR → f_c (from loose to bank) :

$$f_C = \frac{V_B}{V_S} = \frac{\gamma_s}{\gamma_b}$$

moreover: $$f_r = \left(\frac{1}{f_C} - 1\right) \cdot 100$$

EARTHWORKS

TRANSFORMATION COEFFICIENTS/1

WEIGHT* OF MATERIALS	LOOSE kg/m³	LOOSE lb/yd³	BANK kg/m³	BANK lb/yd³	LOAD FACTORS
Basalt	1960	3300	2970	5000	0.67
Bauxite, Kaolin	1420	2400	1900	3200	0.75
Caliche	1250	2100	2260	3800	0.55
Carnotite, uranium ore	1630	2750	2200	3700	0.74
Cinders	560	950	860	1450	0.66
Clay — Natural bed	1660	2800	2020	3400	0.82
Dry	1480	2500	1840	3100	0.81
Wet	1660	2800	2080	3500	0.80
Clay & gravel — Dry	1420	2400	1660	2800	0.85
Wet	1540	2600	1840	3100	0.85
Coal — Anthracite, Raw	1190	2000	1600	2700	0.74
Washed	1100	1850			0.74
Ash, Bituminous Coal	530-650	900-1100	590-890	1000-1500	0.93
Bituminous, Raw	950	1600	1280	2150	0.74
Washed	830	1400			0.74
Decomposed rock —					
75% Rock, 25% Earth	1960	3300	2790	4700	0.70
50% Rock, 50% Earth	1720	2900	2280	3850	0.75
25% Rock, 75% Earth	1570	2650	1960	3300	0.80
Earth — Dry packed	1510	2550	1900	3200	0.80
Wet excavated	1600	2700	2020	3400	0.79
Loam	1250	2100	1540	2600	0.81
Granite — Broken	1660	2800	2730	4600	0.61
Gravel — Pitrun	1930	3250	2170	3650	0.89
Dry	1510	2550	1690	2850	0.89
Dry 6-50 mm (1/4"-2")	1690	2850	1900	3200	0.89
Wet 6-50 mm (1/4"-2")	2020	3400	2260	3800	0.89
Gypsum — Broken	1810	3050	3170	5350	0.57
Crushed	1600	2700	2790	4700	0.57
Hematite, iron ore, high grade	1810-2450	4000-5400	2130-2900	4700-6400	0.85

EARTHWORKS

TRANSFORMATION COEFFICIENTS/2

Limestone — Broken	1540	2600	2610	4400	0.59
Crushed	1540	2600	—	—	—
Magnetite, iron ore	2790	4700	3260	5500	0.85
Pyrite, iron ore	2580	4350	3030	5100	0.85
Sand — Dry, loose	1420	2400	1600	2700	0.89
Damp	1690	2850	1900	3200	0.89
Wet	1840	3100	2080	3500	0.89
Sand & clay — Loose	1600	2700	2020	3400	0.79
Compacted	2400	4050			
Sand & gravel — Dry	1720	2900	1930	3250	0.89
Wet	2020	3400	2230	3750	0.91
Sandstone	1510	2550	2520	4250	0.60
Shale	1250	2100	1660	2800	0.75
Slag — Broken	1750	2950	2940	4950	0.60
Snow — Dry	130	220			
Wet	520	860			
Stone — Crushed	1600	2700	2670	4500	0.60
Taconite	1630-1900	3600-4200	2360-2700	5200-6100	0.58
Top Soil	950	1600	1370	2300	0.70
Taprock — Broken	1750	2950	2610	4400	0.67
Wood Chips**	—	—	—	—	—

EARTHWORKS

TRANSFORMATION COEFFICIENTS/3

SWELL — VOIDS — LOAD FACTORS

SWELL (%)	VOIDS (%)	LOAD FACTOR
5	4.8	0.952
10	9.1	0.909
15	13.0	0.870
20	16.7	0.833
25	20.0	0.800
30	23.1	0.769
35	25.9	0.741
40	28.6	0.714
45	31.0	0.690
50	33.3	0.667
55	35.5	0.645
60	37.5	0.625
65	39.4	0.606
70	41.2	0.588
75	42.9	0.571
80	44.4	0.556
85	45.9	0.541
90	47.4	0.526
95	48.7	0.513
100	50.0	0.500

$$V_s = V_b / f_c$$

$$V_b = V_s / (1 + f_r/100)$$

EARTHWORKS

EQUIPMENT EFFICIENCY

Site-specific efficiency η_c
It is related to the effects, for a given group of units, of the organization of staff devoted to the construction site (i.e. coordination of activities).
It depends upon the number of machines available (thus, machines which work on their own have a higher η_c), on the state of mobility infrastructures in the working site, on supply of consumables, on availability of supporting staff.
It also depends upon equipment type.

Organizzazione del cantiere / Natura dell'attrezzatura	OTTIMA	BUONA	MEDIOCRE	CATTIVA
Attrezzature rimorchiate da trattori a cingoli	0,90	0,87	0,85	0,75
Attrezzature rimorchiate da trattori gommati, Dumper	0,85	0,80	0,75	0,65
Escavatori	0,84	0,81	0,76	0,70

EQUIPMENT FOR EARTHWORKS

Equipment can be distinguished as a function of intended construction work and of specific operation:

- CONSTRUCTION WORK
  1. Clearing and grubbing, removal of topsoil
  2. Excavations (cut sections, ditches, trenches)
  3. Fill (layered construction)
  4. Modelling of subgrades and slopes
  5. Debris removal
  6. Transport

- OPERATION
  a) Excavation and movement
  b) Excavation and loading
  c) Ripping
  d) Transport
  e) Compaction

N.B.
A construction work may require several units; a individual unit may be employed for several construction works

EARTHWORKS

EQUIPMENT EFFICIENCY

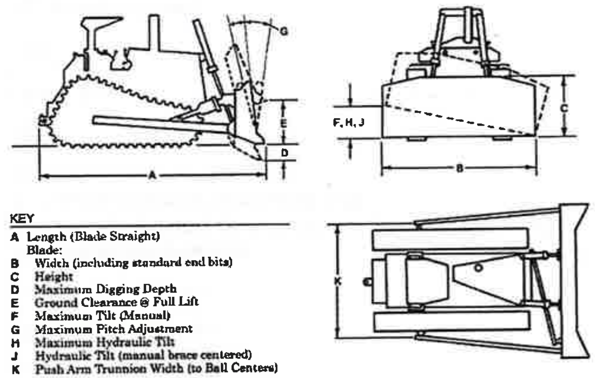
$$\eta = \eta_h \cdot \eta_{cl} \cdot \eta_c$$

η is:

- EXCELLENT	if $\geq$ 75 %
- GOOD	if = 66 %
- SUFFICIENT	if $\cong$ 60 %
- INSUFFICIENT	if < 50 %

EARTHWORKS

DOZER – Construction work/operation: 1,2,3/a



It is a tracked or rubber-wheeld tractor with a forward blade which is controlled in height, tilt and pitch

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EARTHWORKS

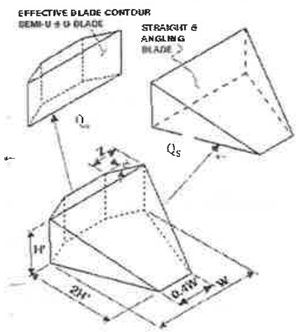
DOZER

Hourly production – analytical method

$$\boxed{P_O = \frac{1}{t_c} \cdot \overline{Q} \cdot \eta}$$

Q is soil quantity measured in <u>loose state</u>

Nominal BLADE CAPACITY (Q) - Simplified method (SAE, *Society Automotive Engineering*)



<u>Straight and Angling Blade Capacity:</u>
$Q = Q_S = 0.8W(H')^2$ (m^3)

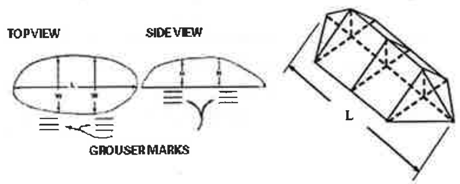
<u>Semi-U and U-Blade Capacity:</u>
$Q = Q_S + Q_U$ (m^3)
$Q_S = 0.8W(H')^2$ (m^3)
$Q_U = ZH'(W-Z) \tan \alpha$ (m^3)

EARTHWORKS

DOZER

Hourly production – analytical method

Measured BLADE CAPACITY (Q) – field method (direct measurement)



$Q = 0.0138 \times (HWL)$ where H,W,L are expressed in feet

EARTHWORKS

DOZER

Hourly production – analytical method

Effective BLADE CAPACITY (Q_e)

$Q_e = Q \times$ fill factor (m^3)

GRANULAR, HOMOGENEUS, DRY	0.8 ÷ 0.9
SOIL - GRAVEL – ORGANIC	0.9 ÷ 1
MIXED GRANULAR WET	1.0 ÷ 1.1
COMPACTED SATURATED CLAY	1.1 ÷ 1.2

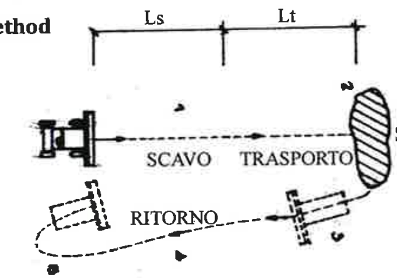
EARTHWORKS

DOZER

Hourly production – analytical method

WORK CYCLE

1) Digging;
2) Formation of soil stockpile;
3) Direction change;
4) Return (unloaded);
5) Direction change



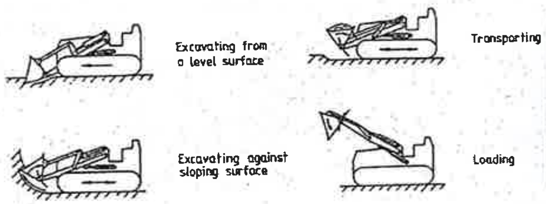
CYCLE TIME

$T_c = (L_s/V_1) + (L_t/V_2) + [(L_s+L_t)/V_3] + T_o + T_m + 2T_p$

L_s = digging length (depends upon model, approximately 6-10 m)
L_t = transport length
V_1 = digging speed (depends upon model, 1st gear forward)
V_2 = transport speed (depends upon model, 2nd gear forward)
V_3 = return speed (depends upon model, 2nd gear reverse)
T_o = time for blade positioning (approximately 1-2 sec)
T_m = time for speed change (approximately 4-5 sec)
T_p = time for direction change (approximately 1.0 sec for each change).

EARTHWORKS

TRACK LOADER



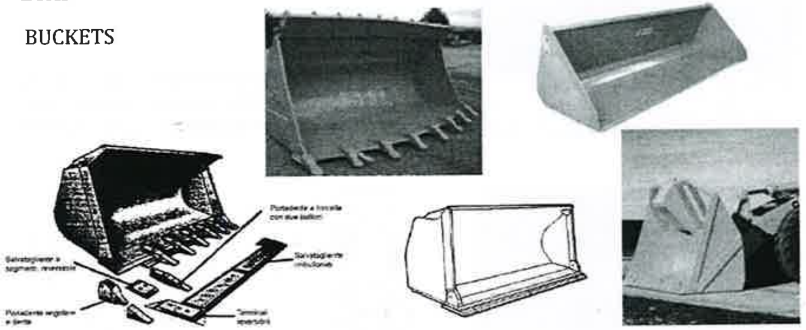
To be preferred on uneven and low bearing capacity soils (low pressure transferred to soil: 0.5-1 kg/cmq).

Slower than wheel loader. Indicated for pushing and trailing operations.

MACCHINE MOVIMENTO TERRA

LOADER

BUCKETS



There are buckets which are specifically designed for different purposes (general use, loose material, bank excavation, rock, waste)

EARTHWORKS

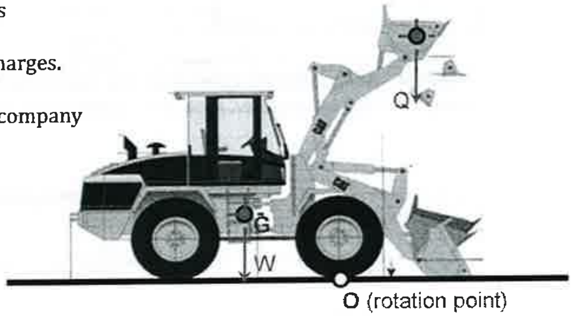
LOADER

TIPPING LOAD

Determined:
- on hard surface
- horizontal plane
- bucket in the maximum extension
- maximum load
- straight and rotated chassis

TL can be increased by surcharges.

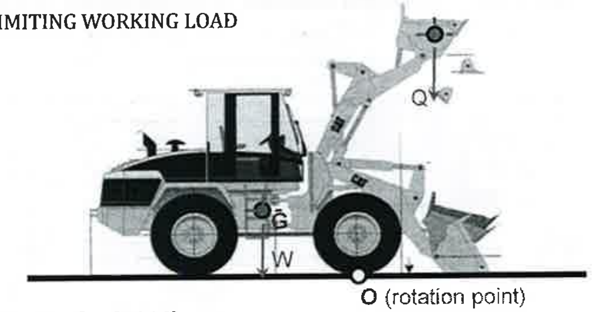
Declared by the production company



EARTHWORKS

LOADER

LIMITING WORKING LOAD



(SAE standard J818)

➢**WHEEL LOADER = 0.5 T.L.**

➢**TRACK LOADER = 0.35 T.L.**

(to be considered in the determination of hourly production)

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EARTHWORKS

LOADER
Hourly production – Analytical method

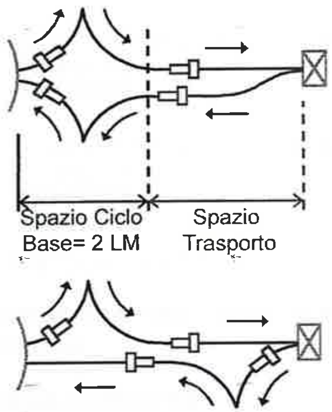
CORRECTIVE FACTORS OF BASE CYCLE TIME

Materials	
— Mixed	+.02
— Up to 3 mm (1/8 in)	+.02
— 3 mm (1/8 in) to 20 mm (3/4 in)	–.02
— 20 mm (3/4 in) to 150 mm (6 in)	–.00
— 150 mm (6 in) and over	+.03 and Up
— Bank or broken	+.04 and Up
Pile	
— Conveyor or Dozer piled 3 m (10 ft) and up	–.00
— Conveyor or Dozer piled 3 m (10 ft) or less	+.01
— Dumped by truck	+.02
Miscellaneous	
— Common ownership of trucks and loaders	Up to –.04
— Independently owned trucks	Up to +.04
— Constant operation	Up to –.04
— Inconsistent operation	Up to +.04
— Small target	Up to +.04
— Fragile target	Up to +.05

EARTHWORKS

LOADER
Hourly production – Analytical method

ADDITIONAL TIME TO BASE CYCLE TIME



$t_t = t_{MANOUVER} + t_{PURE\ TRANSPORT}$

$t_{manouver} = 0.10$ min

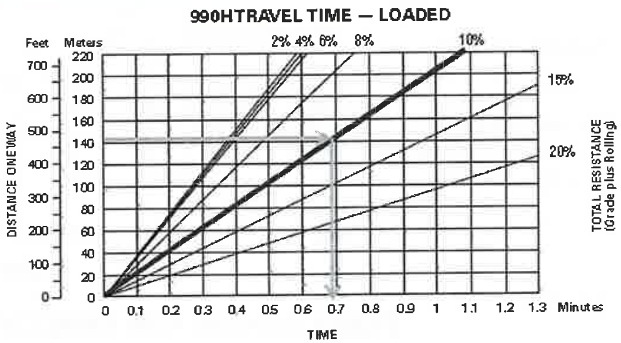
$t_{PURE\ TRANSPORT}$ = Distance/ Speed'
(alternative: charts)

EARTHWORKS

LOADER
Hourly production – Analytical method

ADDITIONAL TIME TO BASE CYCLE TIME (WHEEL LOADER)

GRADE + ROLLING RESISTANCE TR = 10%
DISTANCE = 140 m



EARTHWORKS

LOADER
Hourly production – Analytical method

ADDITIONAL TIME TO BASE CYCLE TIME (WHEEL LOADER)

Total Resistance (TR)=

Rolling Resistance (RR) + Grade Resistance (GR)

RR(%) = 2% + 0.6% per cm tire penetration →

GR(%) = % grade

TR (%) = RR (%) + GR (%)

RR(%)

UNDERFOOTING	Tires Bias	Tires Radial
A very hard, smooth roadway, concrete, cold asphalt or dirt surface, no penetration or flexing	1.5%*	1.2%
A hard, smooth, stabilized surfaced roadway without penetration under load, watered, maintained	2.0%	1.7%
A firm, smooth, rolling roadway with dirt or light surfacing, flexing slightly under load or undulating, maintained fairly regularly, watered	3.0%	2.5%
A dirt roadway, rutted or flexing under load, little maintenance, no water, 25 mm (1") tire penetration or flexing	4.0%	4.0%
A dirt roadway, rutted or flexing under load, little maintenance, no water, 50 mm (2") tire penetration or flexing	5.0%	5.0%
Rutted dirt roadway, soft under travel, no maintenance, no stabilization, 100 mm (4") tire penetration or flexing	8.0%	8.0%
Loose sand or gravel	10.0%	10.0%
Rutted dirt roadway, soft under travel, no maintenance, no stabilization, 200 mm (8") tire penetration and flexing	14.0%	14.0%
Very soft, muddy, rutted roadway, 300 mm (12") tire penetration, no flexing	20.0%	20.0%

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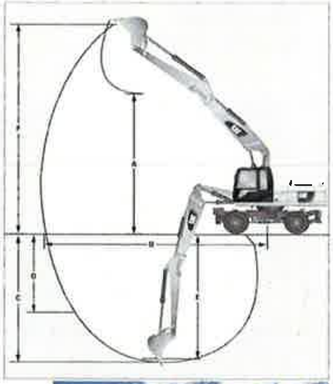
EARTHWORKS

EXCAVATOR – Construction work/operation: 2/b

Constituted by a base equipment with different possible excavating devices.
Rotating chassis mounted on tracks or rubber wheels.

Tracked excavators: can move on uneven terrain with low pressures trasferred to supporting soil (of the order of 0,7 – 0,9 kg/cm^2).
Typical solution for heay and high-power excavators.
Lower center of gravity which increases stability during movement and excavation.



EARTHWORKS

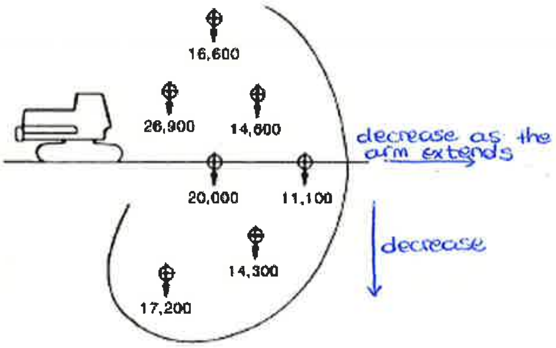
EXCAVATOR – Construction work/operation: 2/b

Rubber wheeled excavators: to be preferred in the case of high mobility and when soil can be damaged by tracks. → they move faster

Excavating device constituted by two arms: base arm connected to the chassis; excavating arm (connected by means of a hinge to the base arm). it allows the excavator → to be articulated
Final bucket.

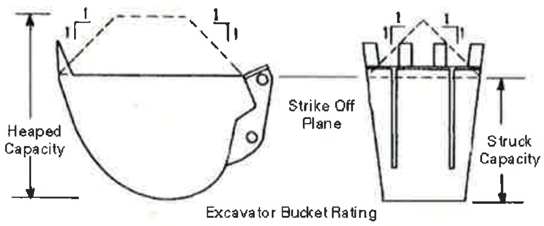
EARTHWORKS

EXCAVATOR (schematic, not scientific)
LOADING CAPACITY (example)



EARTHWORKS

EXCAVATOR
BUCKET CAPACITY



SAE Specifications (standard J-296): ~ tipically 1:1 slope

Struck capacity: volume inside the bucket below *Strike off Plane*.

Heaped Bucket Capacity: previous volume plus volumeabove strike off plane.

Committee on European Construction Equipment (CECE): heaped capacity defined with a 2:1 slope. (on the struck volume)

EARTHWORKS

EXCAVATOR
Hourly production – Analytical method

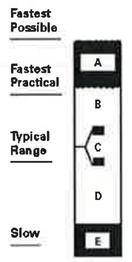
BASE CYCLE TIME

extended cycle time

CYCLE TIME ESTIMATING CHART														
	MACHINE SIZE CLASS													
CYCLETIME	307C 308D CR 308D CR SB	311D	M313D 312D	M315D M316D 315D L	M318D 319D L 319D LN	M322D 320D 320D RR 321D CR 323D	324D	328D LCR	329D	336D	345D	365C L	385C	CYCLETIME
10 SEC.								N/A						0.17 min.
15								N/A						0.25 min.
20 SEC.								N/A						0.33 min.
25														0.42 min.
30 SEC.														0.50 min.
35														0.58 min.
40 SEC.														0.67 min.
45														0.75 min.
50 SEC.														0.83 min.
55														0.92 min.
60 SEC.														1.0 min.

N/A = Not Applicable

fraction of a minute



KEY
A — Excellent
B — Above Average
C — Average
D — Below Average
E — Severe

EARTHWORKS

EXCAVATOR
Hourly production – Analytical method

CORRECTIVE FACTOR (t_f) / 1

MATERIALE	VARIAZIONI CICLO BASE (secondi)
Riserve di materiale o sabbia	-1
Terra ed argilla, misto di argilla e sabbia	0
Argilla dura	+3
Ghiaia in banco	+5
Roccia e massi	+8

angle of unloading

ANGOLO DI SCARICO	VARIAZIONI CICLO BASE (secondi)
0÷45°	0
46÷90°	+1
91÷135°	+2
136÷180°	+3

increase as the rotation.

EARTHWORKS

GRADER – Construction work/operation: 3,4/a

Used for several construction works:
- finishing of slopes;
- surface levelling;
- preparation of sites;
- distribution of loose material;
- pre-ripping;
- snow removal.

versatile equipment

Frame conected to a front axle and to the rear vehicle (with cabin and motor).
Soil levelling occurs with a blade connected to the chassis (different positions).
Distances within 600 m (heavy digging) or up to few km (mean-intensity levelling); penetration of blade occurs in 12÷25 cm with working speeds 4÷24 km/h.

walking speed

EARTHWORKS

GRADER
Hourly production

Depending upon the case, it can be expressed as:
- Volume of soil dug out and positioned in the unit of time [mc/h]; } digging
- Length of profiled track in the unit of time [km/h]; } leveling, profile (different
- Area of levelled surface in the unit of time [mq/h]. } operations)

Calculation of required time:

time required for the operation

$$t = \frac{D}{V \cdot \eta} \cdot n$$

D = distance in km
V = *Operating Speed* in km/h
n = number of passes for operation
η = efficiency ↳ for example for profiling

Operating Speeds:
Typical operating speeds by application

Finish Grading:	0-4 km/h	(0-2.5 mph)
Heavy Blading:	0-9 km/h	(0-6 mph)
Ditch Repair:	0-5 km/h	(0-3 mph)
Ripping:	0-5 km/h	(0-3 mph)
Road Maintenance:	5-16 km/h	(3-9.5 mph)
Haul Road Maintenance:	5-16 km/h	(3-9.5 mph)
Snow Plowing:	7-21 km/h	(4-13 mph)
Snow Winging:	15-28 km/h	(9-17 mph)

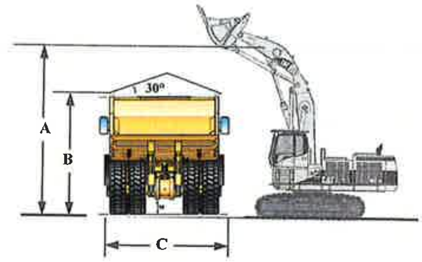
Hourly production **[mc/h]** can be calculated as:

$$P = \frac{A \cdot V}{n} \eta$$

A = area of the transverse working section (efficient length of the blade x digging depth)
→ cross section of the excavating material
↳ different material contributed to the "production"

EARTHWORKS

TRUCKS – DUMPERS
Selection criteria



Optimal loading height:

$$A > B + \frac{C \cdot \tan(30°)}{2}$$

From the technical specification

MODEL	772	
Body Type	Medium Impact Steel Flat Floor	
Gross Machine Weight	[illegible]	[illegible]
Chassis Weight*	25 425 kg	[illegible]
Body Weight	10 439 kg	23,013 lb
Payload Without Liner	46 236 kg	101,934 lb
Standard Liner Weight	—	
Target Payload**	[illegible]	[illegible]
Capacity		
Struck (SAE)	23.3 m³	30.5 yd³
Heaped (2:1) (SAE)	31.3 m³	41.0 yd³
Distribution Empty		
Front	48%	
Rear	52%	
Distribution Loaded		
Front	33%	
Rear	67%	
Engine Model	C18 ACERT	
Number of Cylinders	6	
Bore	145 mm	5.7"
Stroke	183 mm	7.2"
Displacement	18 L	1105 in³
Net Power	399 kW	535 hp
Gross Power	446 kW	598 hp
Standard Tires	21.00R33 (E4)	
Machine Clearance Turning Circle	21.6 m	70'10"
Fuel Tank Refill Capacity	529 L	140 U.S. gal
Top Speed (Loaded)	79.7 km/h	49.5 mph
GENERAL DIMENSIONS (Empty):		
Height to Canopy Rock Guard Rail	4.22 m	13'10"
Wheelbase	[illegible]	[illegible]
Overall Length (Operating)	8.24 m	26'9"
Overall Length (Shipping)	8.74 m	26'9"
Loading Height (Empty)	[illegible]	[illegible]
Height at Full Dump	8.36 m	27'5"
Body Length (Target Length)	5.55 m	16'3"
Width (Operating)	[illegible]	[illegible]
Width (Shipping)***	3.95 m	13'0"
Front Tire Tread	3.17 m	10'5"

Technical characteristics - Example

EARTHWORKS

TRUCKS – DUMPERS
Hourly production

$$\boxed{P_0 = \frac{1}{t_c} \cdot \overline{Q} \cdot \eta}$$

EFFECTIVE BODY CAPACITY

Q = Theoretical capacity x filling factor

(generally declared by producer - Target Payload)

CYCLE TIME

$$\mathbf{t_c = t_{fixed} + t_{variable}}$$

$\mathbf{t_{fixed}}$ → loading time (to be calculated)
manouvering time in loading area = 0.1-0.4 min
unloading time and corresponding manouver = 1.0-1.2 min

$\mathbf{t_{variable}}$ → time required to move from loading to unloading area and viceversa

EARTHWORKS

TRUCKS – DUMPERS
Hourly production

NUMBER OF DUMPERS PER LOADER

$$N_{DUMPERS} = \frac{P_{caricatore}}{P_{dumper}}$$

Il valore ottenuto dovrà essere approssimato all'intero superiore per garantire una produzione richiesta

EARTHWORKS

ROLLERS (COMPACTORS) - Construction work/operation 3, 4 /e

Different types:

- Steel rollers;
- Vibrating;
- Sheep-footed;
- Rubber wheeled.

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31/10/17

POLITECNICO DI TORINO

Construction of Roads, Railways and Airports (01RVMMX)

Exercise

- Settlement prediction

Settlements

CONSOLIDATION SETTLEMENT

Related to the overconsolidation rate
(so to time !!)

TERZAGHI FORMULA → mono dimensional approach

$$\boxed{S_c(t) = H \cdot \frac{C_c}{1+e_0} \cdot \log \frac{\sigma'_{v0} + \Delta\sigma'_v}{\sigma'_{v0}}}$$

Not overconsolidated soil

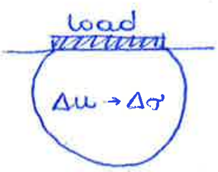
$$\boxed{S_c(t) = H \cdot \frac{\boxed{C_R}}{1+e_0} \cdot \log \frac{\sigma'_{v0} + \Delta\sigma'_v}{\sigma'_{v0}}}$$

Overconsolidated soil

Recompression index

e_0 : input date (easy to valuate void index)
$\Delta\sigma'_v$: because of the load => PROBLEM !!
C_c : consolidation coefficient (TERZAGHI & PECK) $C_c = 0{,}009(w_L - 10)$
H : thickness of compressible layer (=5)

we can't use a graphical approach → it has to be a reliable value



1

Settlements

CONSOLIDATION SETTLEMENT: evaluation of stress increase

Boussinesq approach (stress and strain distribution under vertical concentrated load: *the soil mass is elastic, isotropic, homogeneous and semi-infinite and it is weightless*)

↓

For the linear elasticity we can apply the superposition principle

↓

Various integration of Boussinesq approach to obtain solution for different loads

Different formula for different kind of load

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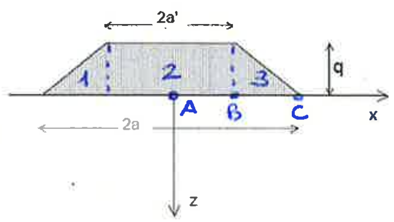
Settlements

CONSOLIDATION SETTLEMENT: evaluation of stress increase

Vertical stress due to vertical trapezoidal load:



Superposition principle: rectangular and triangular loads

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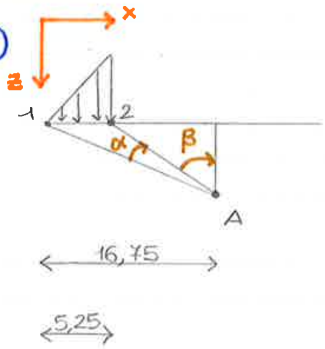
POINT A

(1)



2,5 m → in the middle of the layer

$\overline{12} = \frac{33,5 - 23}{2} = 5,25$

$\beta = arctg\left(\frac{16,75 - 5,25}{2,5}\right) = 1,357$ (radianti)

$\alpha = arctg\left(\frac{16,75}{2,5}\right) - \beta = 0,066$

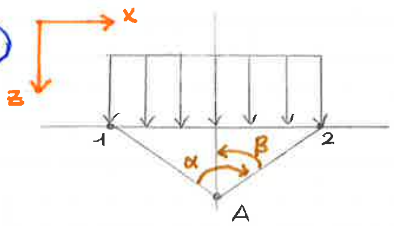
$\sigma'_z = \frac{19,388 \cdot 3,5}{\pi}\left[\frac{16,75}{5,25} \cdot 0,066 - \frac{1}{2} sen(2 \cdot 1,357)\right] = 0,07 \ kN/m^2$

wet density as in the immidiate settlement

we avoid to divide by 2 because of security (safe way even if we have a triangular load instead of rectangular one

$q = \frac{\gamma h}{2}$ it's the real load (in a safe way, we avoid 2)

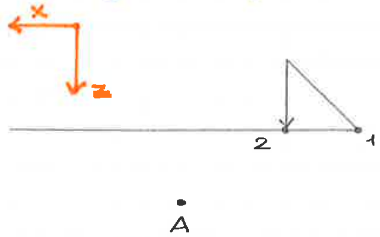
(2)



$\alpha > 0$
$\beta < 0$

$\alpha = 2,713$
$\beta = -1,357$
$\sigma'_z = 67,577 \ kN/m$

(3)



$\alpha = 0,066$
$\beta = 1,357$
$\sigma'_z = 0,07 \ kN/m^2$

$\Rightarrow \Delta\sigma'_v = 0,07 + 67,577 + 0,07 = 67,717 \ kN/m^2$

Settlements

CONSOLIDATION SETTLEMENT

$$\boxed{S_c(t)=H\cdot\frac{C_c}{1+e_0}\cdot\log\frac{\sigma'_{v0}+\Delta\sigma'_v}{\sigma'_{v0}}}$$

→ it changes

- e_0: void index of soft layer = 1,3;
- H: thickness of soft layer; (= 5)
- C_c: consolidation coefficient;
- σ'_{v0}: initial effective stress of the soil at the considered depth;
- $\Delta\sigma'_v$: stress increase due to the presence of embankment.

A) $S_c = 5 \cdot \frac{0,290}{1+1,3} \log \frac{26,5+67,717}{26,5} = 34,7$ cm

B) $S_c = 31,8$ cm

C) $S_c = 8,5$ cm

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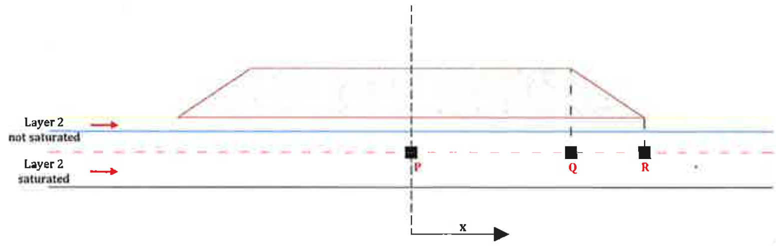
$\Rightarrow S_{c\,TOT} = \frac{34,7+31,8+8,5}{3} = 25$ cm

$S_{TOT} = S_i + S_c = 0,4 + 25 = 25,4$ cm

Settlements

CONSOLIDATION SETTLEMENT

To obtain a reliable value of S_c, the average measurements of peculiar points located in the midpoint line of layer B should be evaluated:



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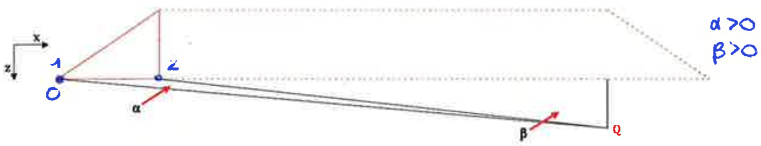
Settlements

CONSOLIDATION SETTLEMENT: evaluation of stress increase $\Delta\sigma'_v$

Point Q:



$$\sigma_z = \frac{q}{\pi}\cdot\left[\frac{x}{B}\cdot\alpha - \frac{1}{2}\cdot\sin(2\beta)\right] \longrightarrow \boxed{\Delta\sigma'_{v,Q1}} = 0{,}014 \ kN/m^2$$

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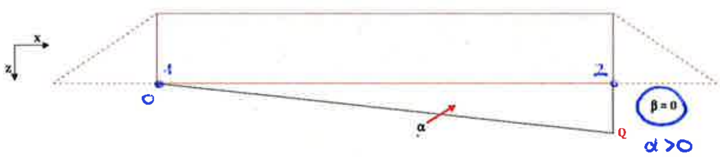
Settlements

CONSOLIDATION SETTLEMENT: evaluation of stress increase $\Delta\sigma'_v$

Point Q:



$$\sigma_z = \frac{q}{\pi}\cdot[\alpha + \sin(\alpha)\cdot\cos(\alpha+2\beta)] \longrightarrow \boxed{\Delta\sigma'_{v,Q2}} = 33{,}911 \ kN/m^2$$

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Settlements

TOTAL SETTLEMENT

$$\boxed{S = S_i + S_c(t)}$$

If it will exceed the maximum allowable value established by the technical specification, we should monitor it to verify the specification requirements

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Settlements

RESIDUAL SETTLEMENT

Remember: when the total settlement exceeds a certain value, we should ensure that at the end of the construction of the embankment the residual settlement will be the 10% of the total settlement expected (in any case less than 5 cm).

$$S_{residual} < 10\% \cdot S$$

$$S_{residual} < 5 \text{ cm}$$

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Settlements

RESIDUAL SETTLEMENT

Time factor

$$\boxed{T_v = \frac{c_v \cdot t}{H_{dr}^2}} = 0,885$$

- c_v: primary consolidation coefficient; $= 3,2 \cdot 10^{-6}\ m^2/s$
- t: time between the beginning of the consolidation and the time at which determine the average consolidation degree (usually the end of the construction of the embankment); = 80 days => from Technical Specifications
- H_{dr}: height of drainage. that each water particle follows to exit to the bound of pression
  ↳ depends on the boundary conditions
  = 5 m

Knowing T_v we can evaluate U_m

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Settlements

RESIDUAL SETTLEMENT

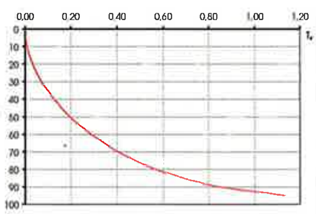
Average consolidation degree

$$\boxed{U_m = \frac{S(t)}{S_c}} = 0,908$$

Sivaram&Swamee

$$\boxed{U_m = \frac{\left(4 \cdot \frac{T_v}{\pi}\right)^{\frac{1}{2}}}{\left[1 + \left(4 \cdot \frac{T_v}{\pi}\right)^{2,8}\right]^{0,179}}}$$

U_m	T_v
0	0
5	0.0017
10	0.0077
15	0.0177
20	0.0314
25	0.0491
30	0.0707
35	0.0962
40	0.1260
45	0.1590
50	0.1960
55	0.2380
60	0.2860
65	0.3420
70	0.4030
75	0.4770
80	0.5670
85	0.6840
90	0.8480
95	1.1290
100	∞



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The degree of consolidation is 90,8% , the consolidation isn't finished.

2/11/17

Politecnico di Torino

Construction of Roads, Railways and Airports

A.Y. 2017/18

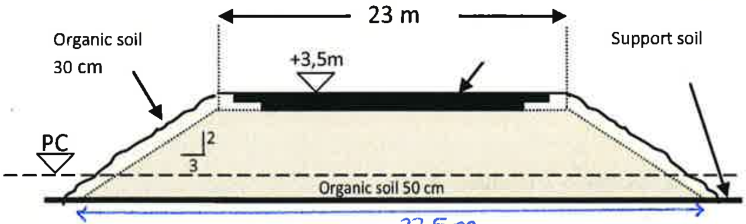
Earthworks planning

4. For the embankment introduced in the Exercise 3, the earthworks planning should be defined. For the hourly production of each machine the Caterpillar Handbook should be used.

REQUEST: evaluate the total time for the construction of the embankment (how many days we need to finish)

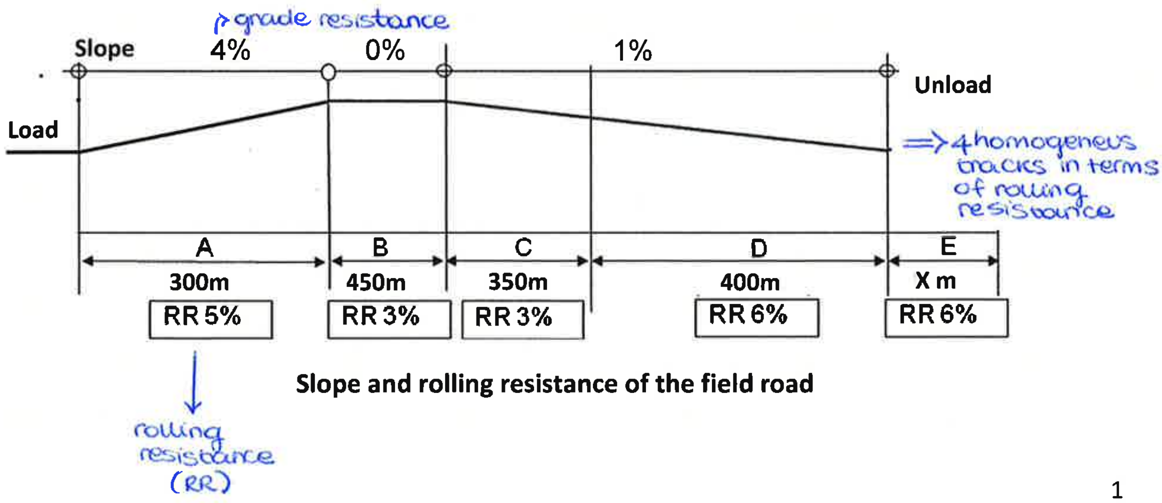
INPUT DATA

The embankment has a length of 1 km and a constant height of 3 m.



SECTION

The soil employed in the embankment construction will be collected at 1.5 km away from the initial section of the new road. A field road will be used for the transport of the soil. Vertical alignment is reported in the following Figure.



Slope and rolling resistance of the field road

- Activity 2D can start at the end of 2C;
- Activity 2A of the subsequent sub-layer will start at the end of the activity 2D of the previous sub-layer.

Work stage n.3:
- Activity 3A will start at the end of the construction of the embankment;
- Dozer and grader may work simultaneously.

GENERAL INFORMATION

Use always the average value of any range of variations.

Soil characteristics

A. Organic soil is a common earth soil:
   - Bank density: 1650 kg/m^3
   - Swelling equal to 22%
   - Number of passing for clearing and compaction of the support layer: 4

B. Soil employed in the construction of the embankment is the same soil used in the Exercise 2:
   - Bank density: 1740 kg/m^3
   - Swelling equal to 11%

C. Thickness of each sub-layer: 50 cm

Work characteristics
↳ efficiency of our system
- General efficiency of the construction site ($\eta_{cl} \cdot \eta_c$): 85% (for wheel loader, dozer and dumper) (grader and roller have an efficiency computed in different ways)
- Hourly efficiency: 50min/60 (for wheel loader, dozer and dumper)
- Working day: 8 hours

Equipment characteristics

Reference: Caterpillar Performance Handbook 46

DOZER type D7R Series 2 (blade 7SU):
- Blade specifications: pp. 19-45
- Travel speed pp. 19-24 (maximum speed) (working speed: digging = 0.75 V_{max}; transport and return 0.85 V_{max})

STEEL ROLLER type CS54B
- Specifications: pp. 13-24
- Efficiency: 0.75
- For the organic soil removal:
   - Number of passes: 4
   - Working speed: 50% of maximum speed
   - Thickness of compaction: 30 cm
- For the compaction of each layer of the embankment: consider 8 passes

POLITECNICO DI TORINO

Construction of Roads, Railways and Airports (01RVMMX)

Excercise

- Part 4

Planning of earthwork operations

→ number of days
→ number of equipment to finish in a certain time

↳ we have to fix the hourly production

Purpose is to design the construction site in terms of:

- Selection of the machine required for each works, evaluating its main characteristics: type, power, number
- Assessment of the cycle of work of each machine
- Arrangement of working charts through which derive the general organization of the yard

Fundamental elements to be taken into account:

- type of action/works
- material (soil) characteristics
- volume of material
- hourly production
- working time

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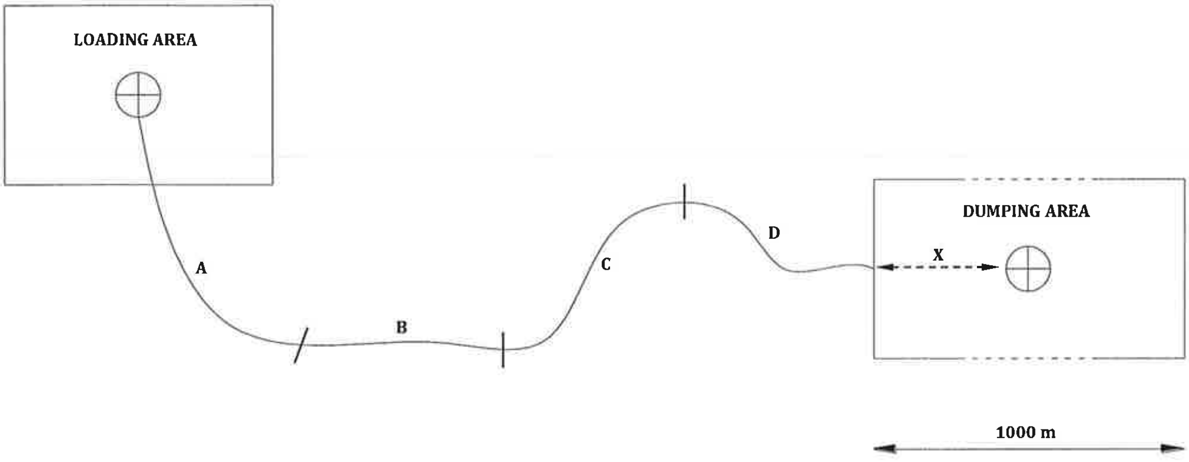
Planning of earthwork operations

Input data

- Path



Planning of earthwork operations

Actions

1. Preparation of the laying surface

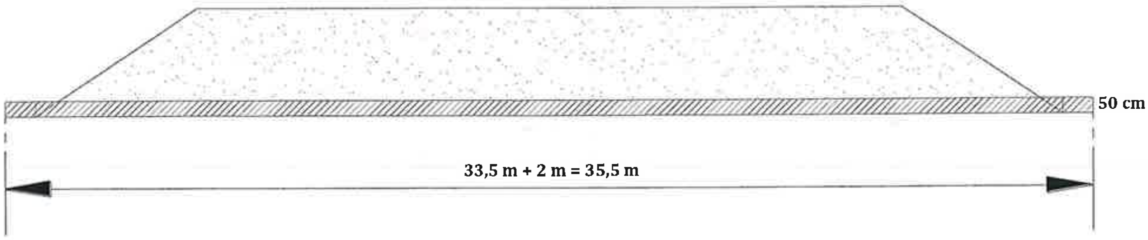
   A. Removal of the organic soil (thickness: 50 cm, width greater than the bottom base of the embankment: 1 m each side);
   ↳ to be sure not to have any contamination of organic soil

   B. Compaction of the bottom of the trench area;

   C. Control operations according to Technical Specifications (1 day).

Planning of earthwork operations

Action 1A: removal of the organic soil



Available equipment: 1 DOZER type D7R Series 2 (blade type 7SU)

Planning of earthwork operations

Action 1A: removal of the organic soil

Theoretical value of production → in ideal conditions

$$\boxed{P_{h,dozer} = \frac{1}{\overline{t}_c} \cdot Q \cdot \eta}$$

- Q = mean quantity moved each cycle [m³] in loose condition → nominal blade capacity ← it has to be defined by the productor
- $\overline{t}_c$ = average time for each cycle[h]
- η = efficiency

→ Blade capacity = 6,86 m³ it's real because it's statically determined

↓

It is preferable to use an effective quantity carried by the blade (Q_e):

$$\boxed{Q_e = Q \cdot \text{fill factor}}$$

DRY GRANULAR MATERIAL	0,8 ÷ 0,9
SOIL - COBBLE - ORGANIC	0,9 ÷ 1,0
WET GRANULAR MATERIAL	1,0 ÷ 1,1
SATURATED COMPACTED CLAY	1,1 ÷ 1,2

⇒ use always the average value for any range

$Q_e = 6{,}86 \cdot 0{,}95 = 6{,}517\ m^3$

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Planning of earthwork operations

Action 1A: removal of the organic soil

- Evaluation of the digging length L_s

$$\boxed{L_d = 2 \cdot B}$$ width

MODEL	D7E 7S LGP		D7R/D7R XR 7SU		D7R/D7R XR 7A		D7R LGP 7S	
Type	Straight		Semi-Universal		Angling		Straight	
Blade Capacities*	6.1 m³	7.9 yd³	6.86 m³	8.98 yd³	3.89 m³	5.07 yd³	5.89 m³	7.7 yd³
Weight, Shipping** (Dozer)	3855 kg	8498 lb	3593 kg	7904 lb	3523 kg	7751 lb	3732 kg	8229 lb
Tractor and Dozer Dimensions:								
A Length (Blade Straight)	6.28 m	20'7"	6.03 m	19'9"	4218 mm	13'10"	5.81 m	19'1"
Length (Blade Angled)	—		—		5098 mm	16'9"	—	
Width (Blade Angled)	—		—		4114 mm	13'6"	—	
Width (with C-Frame only)	—		—		3073 mm	10'1"	—	
Blade Dimensions:								
B Width (including std. end bits)	4.59 m	15'1"	3.69 m	12'1"	4503 mm	14'9"	4.50 m	14'9"
C Height	1351 mm	4'5"	1524 mm	5'0"	1111 mm	3'8"	1343 mm	4'4.9"
D Max. Digging Depth	631 mm	2'1"	527 mm	1'8.7"	647 mm	2'1"	668 mm	2'2.3"
E Ground Clearance @ Full Lift	1292 mm	4'3"	1145 mm	3'9.1"	1340 mm	4'5"	1153 mm	3'9.4"
G Max. Pitch Adjustment	54° to 60°		+3.1° to 3.9°		—		+3.0° to 3.9°	
Blade Angle (either side)	778 mm	2'7"	—		25°			
H Max. Hydraulic Tilt	468 mm	1'7"	799 mm	2'7.4"	466 mm	1'6"	686 mm	2'3"
J Hydraulic Tilt (Manual Brace Centered)	3.35 m	11'0"	474 mm	18.6"	627 mm	2'1"	426 mm	16.8"
K Push Arm Trunnion Width (to Ball Centers)	—		2.87 m	9'5"	2795 mm	9'2"	3.37 m	11'1"

Ld = 7,38 m

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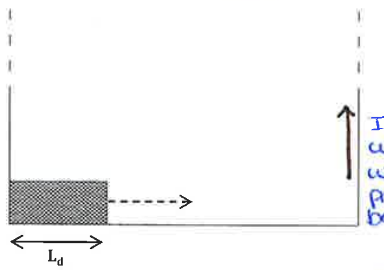
Planning of earthwork operations

Action 1A: removal of the organic soil

- Evaluation of the average transport length L_t

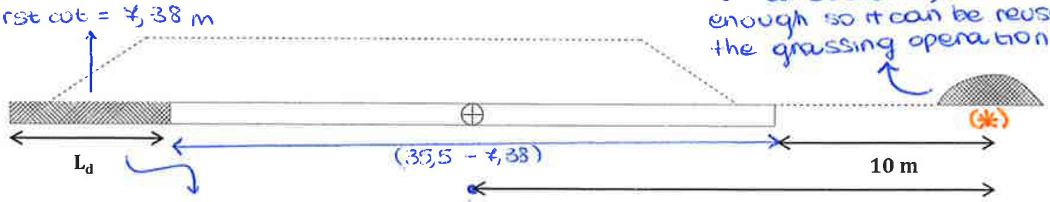
↳ we have to decide how the dozer works, it's up to the design



It can also work in this way, but in this problem it's better horizontally → Transverse section (left to right)

first cut = 7,38 m

not an obstacle, but near enough so it can be reused for the grassing operation



remove topsoil, stop cutting and transport (✱)

$$\frac{35{,}5 - 7{,}38}{2} \qquad = \frac{33{,}5 + 2 - 7{,}38}{2} + 10$$

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⟹ for each cutting Lt changes but it's too complicated so we consider an average value, so we can always use this number

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Planning of earthwork operations

Action 1A: removal of the organic soil

- Evaluation of P_h

↳ we need time, not the hourly production

$$\boxed{P_{h,dozer} = \frac{1}{t_c} \cdot Q \cdot \eta} = \frac{1}{51,7} \cdot 6,517 \cdot 0,708 = 0,089 \ m^3/s$$

$= 321,3 \ m^3/h$

- Evaluation of the total volume to remove $V_{b,remove}$

$$\boxed{V_{b,remove} = l_{dig} \cdot L_{dig} \cdot h_{dig}}$$

$= 35,5 \cdot 1000 \cdot 0,5 = 17'750 \ m^3$

it's bank volume (natural compaction)

It is a bank volume, the hourly production was evaluated in loose conditions:

↳ From bank to loose we observe an increase of volume

$$\boxed{V_{loose,remove} = V_{b,remove} \cdot (1 + f_s)}$$

$= 17'750 \ (1 + 0,22) = 21'655 \ m^3$

Planning of earthwork operations

Action 1A: removal of the organic soil

- Total time for the action T_{1A}

↳ we can evaluate it because we divide the same kind of soil (loose over loose)

$$\boxed{T_{1A} = \frac{V_{loose,remove}}{P_{h,dozer}}} = \frac{21'655}{321,3} = 67,4 \ h$$

$\frac{67,4}{8} \simeq 9$ days

Planning of earthwork operations

Action 1B: regularization and compaction

- Total volume to be compacted $V_{b,compaction}$

$$V_{b,compaction} = l_{dig} \cdot L_{dig} \cdot h_{dig}$$ → in bank condition

$= 35{,}5 \cdot 1000 \cdot 0{,}3 = 10'650\ m^3$

- Time needed for the action T_{1B}
  ↳ we can compute it without transforming the volume

$$T_{1B} = \frac{V_{b,compaction}}{P_{h,roller}}$$ → in bank condition

$= \frac{10'650}{666{,}2} = 16h \Rightarrow 2$ working days

Action 1C: quality control

FIELD TEST

- Control operations time T_{1C}: 1day
  ↳ day to obtain results (one day after compaction)

we can't sum $T_{1A}+T_{1B}+\ldots$ because different activities can be done at the same time, simultaneously
↳ At the end we use also other safety factors

⇒ Finish of the first activity

Planning of earthwork operations

↳ loading and construction of the embankment (transport, compaction, ecc.)

EMBANKMENT CONSTRUCTION

Action 2A: transport of soil for the formation of each layer of the embankment from storage to construction area

≠ layers of 50 cm

we have to define the primary action (LOADING) which gives the days we need

Combined use of two machine:

- 1 WHEEL LOADER type 988K with 347-4980 bucket (General Purpose Bucket)
- n ARTICULATED TRUCKS type 725C (transport of material)
  ↳ we need the right number of trucks which allows the hourly production of the loader

Planning of earthwork operations

Action $2A_1$: loading the soil on dumper

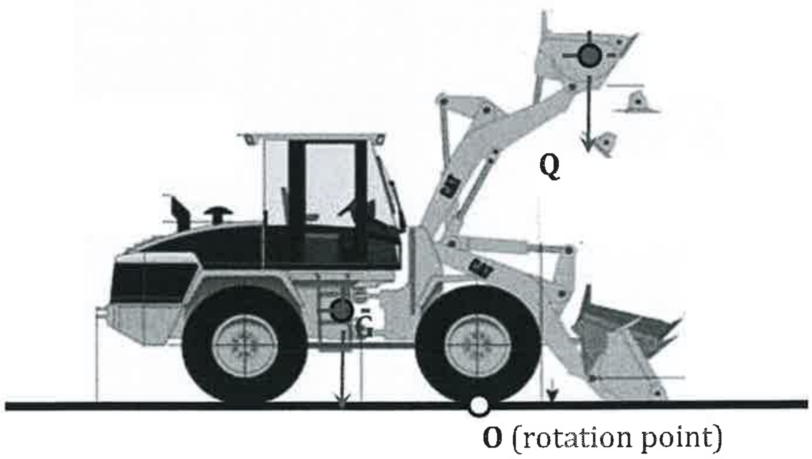
- Evaluation of Q_e: consider the soil properties

Loose material	
Mixed moist aggregates	95÷100%
Uniform aggregates up to 3 mm	95÷100%
3 mm to 9 mm	90÷95%
12 mm to 20 mm	85÷90%
24 mm and over	85÷90%
Blasted rock	
Well blasted	80÷95%
Average	75÷90%
Poor	60÷75%
Other	
Rock dirt mixtures	100÷120%
Moist loam	100÷110%
Soil, boulders, roots	80÷100%
Cemented materials	85÷95%

Planning of earthwork operations

Action $2A_1$: loading the soil on dumper

- Tipping check

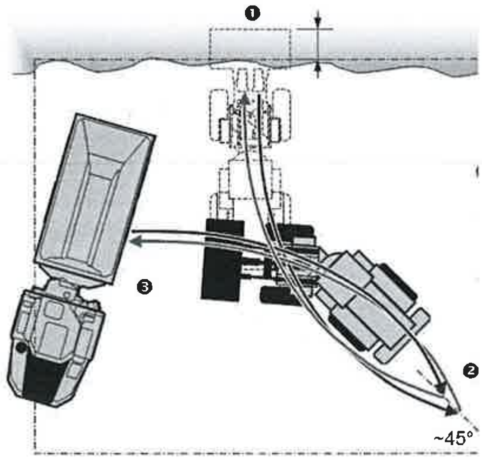


Planning of earthwork operations

Action 2A_1: loading the soil on dumper

- Evaluation of $\overline{t_c}$

$$\overline{t}_c = t_{cb} + t_f + t_t$$



- t_{cb} = cyclic base time (loading time, unloading time and time for the basic movements in the minimum working area)
- t_f = corrective factor of t_{cb}
- t_t = additional time for movements outside the minimum working area (it's up to the designer)

Planning of earthwork operations

Action 2A_1: loading the soil on dumper

- t_{cb}

  For wheel loader: 0,45 ÷ 0,55 minutes

- t_f

Materials	
Mixed	+0,02 min
Up to 3 mm	+0,02 min
3 mm to 20 mm	-0,02 min
20 mm to 150 mm	±0,00 min
150 mm and over	+0,03 and up min
Bank or broken	+0,04 and up min

the constructor usually works with this machines (it isn't a problem for the worker)

Pile	
Conveyor or Dozer piled 3 m and up	±0,00 min
Conveyor or Dozer piled 3 m or less	+0,01 min
Dumped by truck	+0,02 min
Miscellaneous	
Common ownership of trucks and loaders	up to -0,04 min
Independently owned trucks	up to +0,04 min
Constant operations	up to -0,04 min
Inconsistent operation	up to +0,04 min
Small target	up to +0,04 min
Fragile target	up to +0,05 min

- t_t: 0

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$\frac{P_L}{P_{TL}} < 0,5$ → weight in the bucket; P_{TL} → maximum load allowed

$P_L = V(621) \cdot 1567,6\ kg/m^3\ (\text{loose}) = 9734,8\ kg$

$P_{TL} = 29740\ kg$

$\frac{\text{bank density}}{1+f_r} = \text{loose density}$

$\gamma_L = \frac{1740}{1+0,11} = 1567,6\ kg/m^3$

Planning of earthwork operations

$\frac{P_L}{P_{TL}} = \frac{9734,8}{29740} = 0,33 < 0,5$

f_r: filling factor (= 11%)

9/11/17

Action $2A_1$: loading the soil on dumper

- Calculation of the time needed to load the soil used for the formation of each sub-layer

compacted volumes ← from external actions

$V_1 = 16375\ m^3$

$V_2 = 15625\ m^3$

$V_3 = 14875\ m^3$

$V_4 = 14125\ m^3$

$V_5 = 13375\ m^3$

$V_6 = 12625\ m^3$

$V_7 = 11875\ m^3$

$$\boxed{t_{2A_{1\,\text{ith-layer}}} = \frac{V_{\text{ith-layer}}}{P_{h,\text{loader}}}}$$

we have to compute the volume of each of the 7 layers

$P_{h,\text{loader}}$ → loose material

$33,5 - (0,5 \cdot \frac{3}{2}) \cdot 2 = 32$ so $V_1 = \frac{(33,5+32)}{2} \cdot 0,5 \cdot 1000$

- Evaluation of the total time required for the action T_{2A1}

$$\boxed{T_{2A_1} = \sum_{i=1}^{n} t_{2A_{1\text{ith-layer}}}}$$

→ it's referred to a certain number of trucks

n: number of layer

from bank to loose we use filling factor

from loose to compaction we use a coefficient which depends on the degree of compaction (c)

$V_L = V_c(1+c)$

$c = \frac{\gamma_c}{\gamma_L} - 1 = 0,19$

we can use the same value as 95% of the dry density of the material we study using the proctor

$\gamma_c = 0,95 \cdot 1,967 = 1,869\ g/cm^3$

(*) →

Planning of earthwork operations

The loader never stops so we have to compute the correct number of trucks to allow it.

Action $2A_2$: transport of material from loading to dumping area

$$\boxed{P_{h,\text{truck}} = \frac{1}{\bar{t}_c} \cdot Q \cdot \eta}$$

Follow the hand book

- Q = effective capacity $[m^3]$ in loose condition $= 15,0\ m^3 \cdot \underbrace{\text{fill factor}}_{0,9} = 13,5$
- $\bar{t}_c$ = average time for each cycle[h]
- η = efficiency

(*) ←

$V_{1L} = 19486\ m^3 \rightarrow 32,5h = 5$ days

$V_{2L} = 18593,8\ m^3 \rightarrow 4$ days

$V_{3L} = 17701,25\ m^3 \rightarrow 4$ days

$V_{4L} = 16808,8\ m^3 \rightarrow 4$ days

$V_{5L} = 15916,3\ m^3 \rightarrow 4$ days

$V_{6L} = 15023,8\ m^3 \rightarrow 4$ days

$V_{7L} = 14131,3\ m^3 \rightarrow 3$ days

Planning of earthwork operations

Action $2A_2$: transport of material from loading to dumping area

- Evaluation of the effective capacity of the truck (Q_e)

MODEL	725C	
Gross Power – SAE J1995	239 kW	320 hp
Net Power – SAE J1349	234 kW	314 hp
Net Power – ISO 14396	236 kW	316 hp
Net Power – EEC 80/1269	236 kW	316 hp
Operating Weight (Empty)*	23 220 kg	51,191 lb
Top Speed (Loaded)	56 km/h	35 mph
GMW – Gross Machine Weight	46 820 kg	103,220 lb
Distribution Empty:		
Front	62.1%	
Center	19.6%	
Rear	18.3%	
Distribution Loaded:		
Front	36.1%	
Center	32.3%	
Rear	31.6%	
Max. Capacity**	23.6 t	26T
Struck (SAE)	11 m³	14.4 yd³
Heaped (2:1) (SAE)	15 m³	19.6 yd³
Tailgate Heaped SAE 2:1	15.6 m³	20.4 yd³
Tailgate Struck	11.1 m³	14.5 yd³
Engine Model	C9.3 ACERT	
No. Cylinders	6	
Bore	115 mm	4.53"
Stroke	149 mm	5.87"
Displacement	9.3 L	567 in³
Tires, Front, Center, Rear	23.5R25 Radials	
Circular Clearance Diameter	16.2 m	53'0"
Fuel Tank Refill Capacity	410 L	108.3 U.S. gal
DEF Tank Capacity	20 L	5.3 U.S. gal
General Dimensions (Empty):		
Height to Cab Top	3.47 m	11'4"
Wheel Base (Front-Center of Bogie)	4.83 m	15'8"
Overall Length	10.45 m	34'3"
Loading Height (Empty)	2.73 m	8'9"
Height at Full Dump	6.31 m	20'7"
Body Length	5.69 m	18'7"
Width (Operating – Over Mirrors)	3.70 m	12'2"
Front Tire Tread	2.28 m	7'5"

It is a theoretical capacity

$$\boxed{Q_e = Q \cdot \text{fill factor}}$$

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Planning of earthwork operations

Action $2A_2$: transport of material from loading to dumping area

- Checking the target payload

$$\boxed{Q_e \cdot \gamma_s < P_{\text{target payload}}}$$

MODEL	725C	
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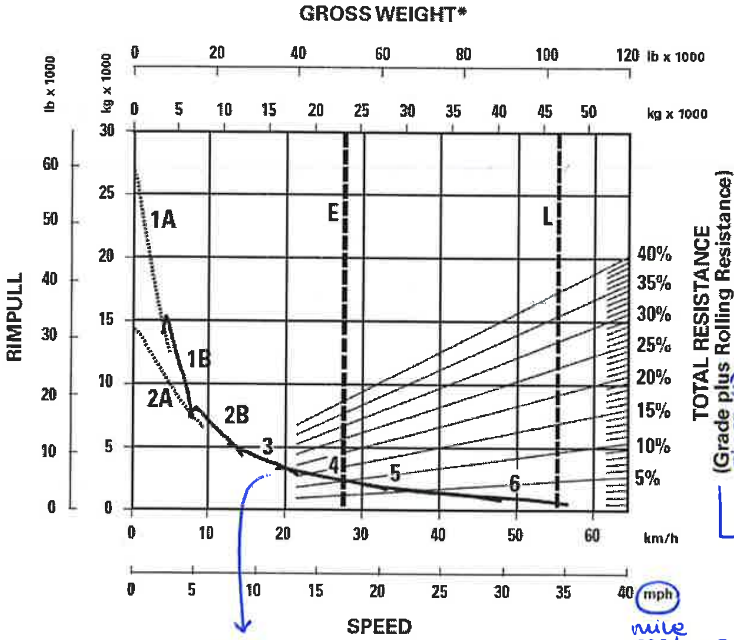
Planning of earthwork operations

Action $2A_2$: transport of material from loading to dumping area

- Evaluation of $\overline{t}_c$: calculation of $t_{variable}$



L: loading weight (from loading area to construction)
E: empty weight (from construction to loading area)

percentage of the weight of the truck

Knowing the weight we reach the total resistance than horizontal line until the gear curve, so the abscissa of this point is the speed of the truck in this action.

Planning of earthwork operations

Action $2A_2$: transport of material from loading to dumping area

- Evaluation of $\overline{t}_c$: calculation of $t_{variable}$

Example - way on path A:

R = RR + i = 5 + 4% = 9%

Loading
L = 300 m
V = 17,5 km/h
L/V = 61,7 s

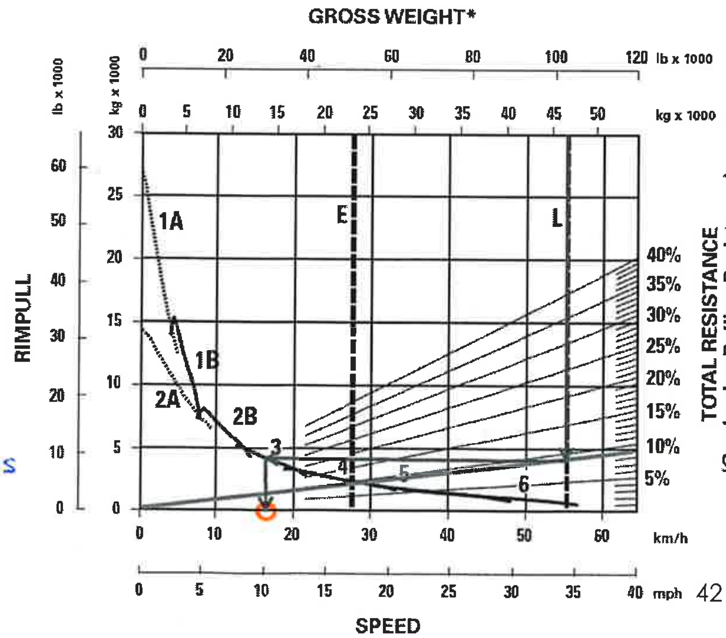
(B) TR = 3%
L = 450 m
V = 40 km/h
L/V = 40,5 s

(C) TR = 2%
L = 350 m
V = 53 km/h
23,7 s

(D) TR = 6% - 1% = 5%
L = 400 m
V = 30 km/h
48,0 s

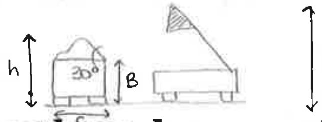
(E) TR = 6%
L = 500 m
V = 24 km/h
75,6 s

TOT = 249,5 s



grade resistance = slope (i)
i + RR

Evaluate that truck and loader can work together



$h = B + \frac{C}{2} \operatorname{tg} 30°$

$C^* = 3{,}70 - 2 \cdot 0{,}35 = 3\,m$

width over mirror — mirrors

$h = 3{,}60\ m$, $H = 3{,}894\ m$ } $H > h$

Planning of earthwork operations

Action 2B: formation of each layers

not important the hourly product, but time (for activities without cut and transport)

Available machine: 1 GRADER type 140M

most versatile machine (snow, grubbing, spread, create particular shape)

Planning of earthwork operations

Action 2B: formation of each layers

The hourly production is governed by the material dumped in the dumping area (and so by the wheel loader) → we should know the time needed for the formation of each layer:

$$\boxed{t_{\text{ith-layer}} = \frac{D}{V \cdot \eta} \cdot n}$$

nothing related to the geometry of our equipment
↳ anything

- D: length in km
- V: working speed in km/h (for a particular work)
- n: number of passes on each point to have a finite and clean layer
- η: efficiency

because we have an overlap between different layers.

number the grader should pass to cover all the surface (the time is for a length equal to the width of the blade) → $\frac{\text{bottom width of layer}}{\text{width of blade}} = n$

1 layer) $n = \frac{33{,}5}{3{,}658} = 9{,}2 \Rightarrow 10$ for each passes we need 2 passes for the spreading and two passes for the finishing

2) 9 3) 9 4) 8 5) 8 6) 8 7) 7

=> we need time to compact each layer with roller

Planning of earthwork operations

Action 2C: compaction of each layer

$$P_{h,roller} = \frac{L \cdot V \cdot H}{P} \cdot \eta$$

- L = width of compaction[m]
- V = compaction speed [km/h] = 50% maximum speed
- H = thickness of compacted layer[mm] = 50 cm
- P = number of passes at each point to reach exact density = 8
- η = efficiency: indicative value of 0.75 (considering a partial overlap of 10-15cm).

we have L, related to the geometry of the roller so we don't have to evaluate number of continous passes (it's simply P = 8 → evaluated by experience or trial section, before construction)

$P_{H,roller} = 555{,}2 \ m^3/h$

MODEL	CS54B*	
Gross Power	98 kW	131 hp
Rated Engine RPM	2200	
No. Cylinders	4	
Displacement	4.4 L	268 in³
Engine Model	C4.4 ACERT	
Emission Standards	Tier 4 Final/Stage IV	
Speeds	2 forward/2 reverse	
Max. Speed (For./Rev.)	11.1 km/h	6.8 mph
Approximate Operating Weight	10 555 kg	23,265 lb
Drive	Drum/Rear Wheel	
Steering:		
Inside Radius	3680 mm	12'1"
Outside Radius	5810 mm	19'1"
Steering Angle	±34°	
Vibratory System:		
Ecc. Weight Drive	Hydraulic	
Frequency[3]	30.5 Hz	1830 vpm
Amplitude:	2	
High Amplitude	1.90 mm	0.075"
Low Amplitude	0.95 mm	0.037"
Centrifugal Force:		
Maximum	234 kN	52,600 lb
Minimum	133 kN	29,900 lb
General Dimensions:		
Overall Width with Blade	—	
Overall Width without Blade	2300 mm	7'7"
Drum Width	2134 mm	7'0"
Drum Diameter	1534 mm	5'0"
Tires	23.1 × 26 — 8 ply floatation	
Overall Height	3110 mm	10'3"
Wheel to Drum	2900 mm	9'7"
Overall Length	5850 mm	19'2"
Curb Clearance	543 mm	21.4"
Service Refill Capacities:		
Fuel Tank	242 L	64 U.S. gal
Diesel Exhaust Fluid Refill Capacity	15 L	4 U.S. gal
Crankcase	8.8 L	2.3 U.S. gal
Hydraulic Fluid	50 L	13.2 U.S. gal

Planning of earthwork operations

Action 2C: compaction of each layer

- Evaluation of the compacted volume $V_{b,compaction\ ith\text{-}layer}$ of each layer

$$V_{b,compaction_{ith\text{-}layer}} = V_{c,ith-layer} \ \text{(slide 32)}$$

1) $\frac{16{,}375}{555{,}2} = 29{,}5h$ = 4 days
2-5) 4 days
6-7) 3 days

- Evaluation of total time needed for the compaction of each layer

$$t_{2C_{ith\text{-}layer}} = \frac{V_{b,compaction_{ith\text{-}layer}}}{P_{h,roller}}$$

→ in compacted state

- Total time for the Action 2C T_{2C}

$$T_{2C} = \sum_{i=1}^{n} t_{2C_{ith-layer}}$$

n: number of layers

Planning of earthwork operations

Action $3A_1$: transport of the material from storage area to escarpment (slope)

$$\boxed{P_{h,dozer} = \frac{1}{\bar{t}_c} \cdot Q \cdot \eta}$$

- Q = mean quantity moved each cycle [m^3] in loose condition
- $\bar{t}_c$ = average time for each cycle[h] $= \frac{LD}{VD} + \frac{LT}{VD} + \frac{LT + LD}{VR} + \underbrace{+T_o + T_m + 2T_p}_{\text{as the dozer before}}$ 3 constant terms
- η = efficiency $= 0{,}708$

10m

digging doesn't happens this time — transport — return

It is preferable to use an effective quantity carried by the blade (Q_e):

$$\boxed{Q_e = Q \cdot \text{fill factor}}$$

$= 6{,}517\ m^3$

DRY GRANULAR MATERIAL	0,8 ÷ 0,9
SOIL - COBBLE – ORGANIC	0,9 ÷ 1,0
WET GRANULAR MATERIAL	1,0 ÷ 1,1
SATURATED COMPACTED CLAY	1,1 ÷ 1,2

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$$t_c = \frac{10}{\frac{5{,}165}{3{,}6}} + \frac{10}{\frac{6{,}675}{3{,}6}} + 1{,}5 + 4{,}5 + 2 \cdot 1 = 20{,}3\ s$$

Planning of earthwork operations

Action $3A_1$: transport of the material from storage area to escarpment (slope)

- <u>Evaluation of Q_e</u>

	D7E		D7R/D7R XR				D7R LGP	
MODEL	7S LGP		7SU		7A		7S	
Type	Straight		Semi-Universal		Angling		Straight	
Blade Capacities*	6.1 m³	7.9 yd³	6.86 m³	8.98 yd³	3.89 m³	5.07 yd³	5.89 m³	7.7 yd³
Weight, Shipping** (Dozer)	3855 kg	8498 lb	3593 kg	7904 lb	3523 kg	7751 lb	3732 kg	8229 lb
Tractor and Dozer Dimensions:								
A Length (Blade Straight)	6.28 m	20'7"	6.03 m	19'9"	4218 mm	13'10"	5.81 m	19'1"
Length (Blade Angled)	—		—		5098 mm	16'9"	—	
Width (Blade Angled)	—		—		4114 mm	13'6"	—	
Width (with C-Frame only)	—		—		3073 mm	10'1"	—	
Blade Dimensions:								
B Width (including std. end bits)	4.59 m	15'1"	3.69 m	12'1"	4503 mm	14'9"	4.50 m	14'9"
C Height	1351 mm	4'5"	1524 mm	5'0"	1111 mm	3'8"	1343 mm	4'4.9"
D Max. Digging Depth	631 mm	2'1"	527 mm	1'8.7"	647 mm	2'1"	668 mm	2'2.3"
E Ground Clearance @ Full Lift	1292 mm	4'3"	1145 mm	3'9.1"	1340 mm	4'5"	1153 mm	3'9.4"
G Max. Pitch Adjustment	54° to 60°		+3.1° to 3.9°		—		+3.0° to 3.9°	
Blade Angle (either side)	778 mm	2'7"	—		25°			
H Max. Hydraulic Tilt	468 mm	1'7"	799 mm	2'7.4"	466 mm	1'6"	686 mm	2'3"
J Hydraulic Tilt (Manual Brace Centered)	3.35 m	11'0"	474 mm	18.6"	627 mm	2'1"	426 mm	16.8"
K Push Arm Trunnion Width (to Ball Centers)	—		2.87 m	9'5"	2795 mm	9'2"	3.37 m	11'1"

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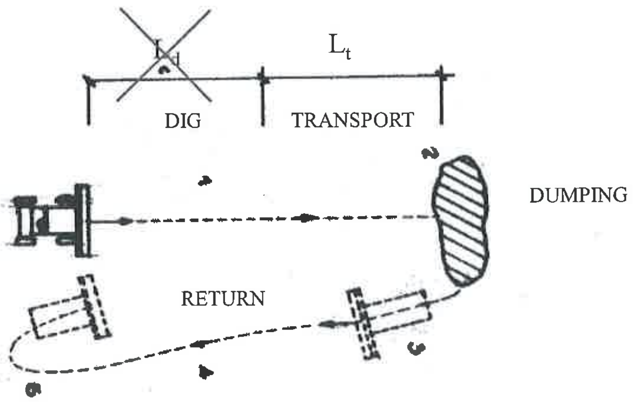
Planning of earthwork operations

Action $3A_1$: transport of the material from storage area to escarpment (slope)

- Evaluation of $\bar{t}_c$



$$\bar{t}_c = \cancel{\frac{L_d}{V_1}} + \frac{L_t}{V_2} + \frac{\cancel{L_d} + L_t}{V_3} + T_o + T_m + 2T_p$$

Planning of earthwork operations

Action $3A_1$: transport of the material from storage area to escarpment (slope)

- Evaluation of the working speedV_1 and V_2

POWER SHIFT MODEL	D5R2 Powershift with AutoShift		D6R2 Powershift with AutoShift		D6T		D7E		D7E LGP		D7R	
FORWARD	km/h	mph	km/h	mph	km/h	mph	km/h	mph	km/h	mph	km/h	mph
1	3.3	2.1	3.8	2.4	3.8	2.3	—	—	—	—	3.52	2.19
1.5	4.2	2.6	4.8	3.0	—	—	—	—	—	—	—	—
2	5.8	3.6	6.5	4.1	6.5	4.0	—	—	—	—	6.10	3.79
2.5	7.3	4.5	8.4	5.2	—	—	—	—	—	—	—	—
3	10.1	6.3	11.5	7.1	11.3	7.0	—	—	—	—	10.54	6.55
REVERSE												
1	4.2	2.6	4.8	3.0	4.7	2.9	—	—	—	—	4.54	2.82
1.5	5.2	3.2	6.2	3.9	—	—	—	—	—	—	—	—
2	7.3	4.5	8.4	5.2	8.3	5.1	—	—	—	—	7.85	4.88
2.5	7.3	4.5	8.4	5.2	—	—	—	—	—	—	—	—
3	12.5	7.8	14.5	9.1	14.6	9.0	—	—	—	—	13.58	8.44
ELECTRIC												
FORWARD	—	—	—	—	—	—	11.3	7.0	11.3	7.0	—	—
REVERSE	—	—	—	—	—	—	11.3	7.0	11.3	7.0	—	—

→ maximum speed

Working speeds are lower:

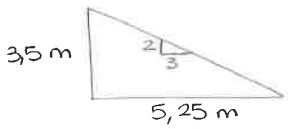
- $V_2 = 0{,}85\ V_{max,2nd\ gear}$ for transport;
- $V_3 = 0{,}85\ V_{max,2nd\ reverse\ gear}$ for the empty return .

Planning of earthwork operations

Action $3A_1$: transport of the material from storage area to escarpment (slope)

- Total time for the Action 3A1 T_{3A1}

$$\boxed{T_{3A_1} = \frac{V_{loose,grassing}}{P_{h,dozer}}} = \frac{4611,6\ m^3}{818,3} = 5,6\ h = 1\ day$$



real length of slope

$V_{grassing} = (6,3 \cdot 1000 \cdot 0,3) = 1890\ m^3 \times 2 = 3780\ m^3 \Rightarrow$ it isn't loose!

typical value for grassing

we need two volumes

The grader makes the soil similar to a natural compacted (not really compacted)
So we need swelling coefficient to pass from this volume to loose material so we can compute hourly production which is expressed in terms of loose soil
$V_L = 3780(1+0,22) = 4611,6\ m^3$

Planning of earthwork operations

Action $3A_2$: shaping of escarpments (slopes) to cover all the surface

Available machine: 1 GRADER type 140M 1 operation 2 passes

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Planning of earthwork operations

Action $3A_2$: shaping of escarpments

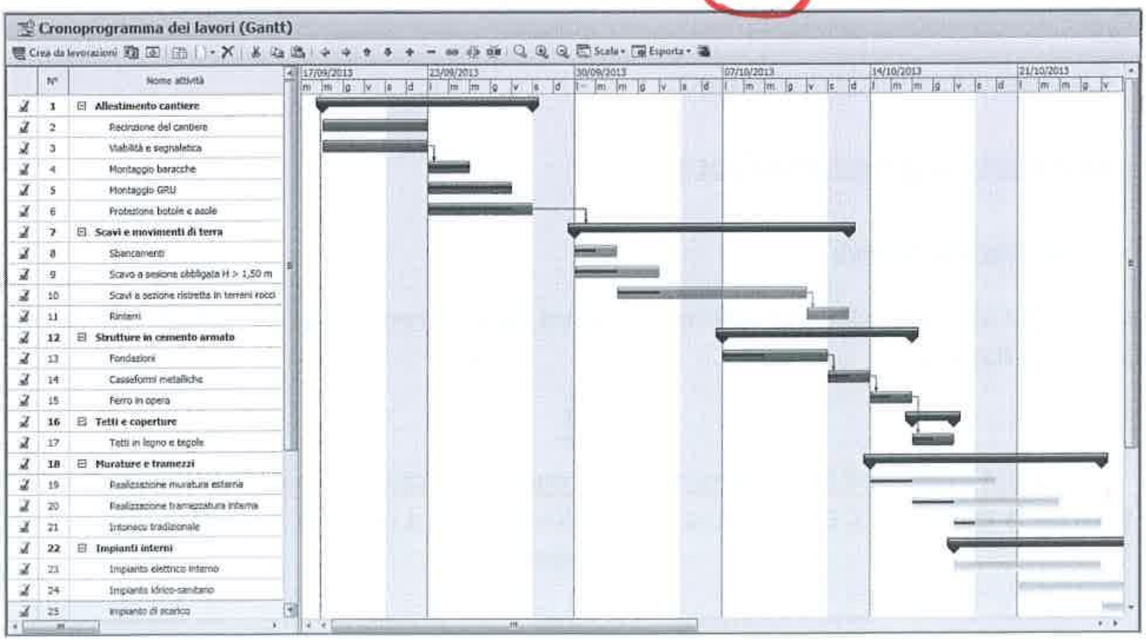
- Total time for the Action 3A2 T_{3A2}

$$\boxed{T_{3A_2} = \frac{D}{V \cdot \eta} \cdot n}$$

Earthworks total time

Some actions can be performed at the same time

Working schedule may be presented by means of the GANTT diagram:



Earthworks total time

Actions

1. Preparation of the laying surface

   A. Removal of the organic soil
   B. Compaction of the bottom of the trench area
   C. Field control (which not depends on the other two)

2. Construction of the embankment

   A. Transport of the soil required for the formation of each sub-layer of the embankment (loading and transportation)
   B. Formation of the sub-layer (spreading)
   C. Compaction of the sub-layer

3. Escarpments/slopes

   A. Transport of the material
   B. Grassing of slopes

Earthworks total time

Actions

- Primary activity duration: T_A
- Secondary activity duration: T_B

RULES:

Theoretical method:

1. If $T_A > T_B \rightarrow$ secondary activity can not finish before the primary one

we use the finish of the primary action as the ending point of the second one

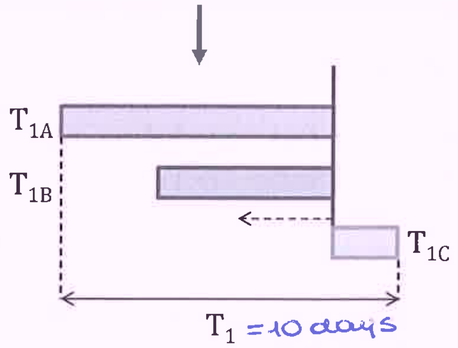
or

Earthworks total time

Action 1

1.Preparation of the laying surface

$T_{1A} > T_{1B} \rightarrow$ secondary activity can not finish before the primary one

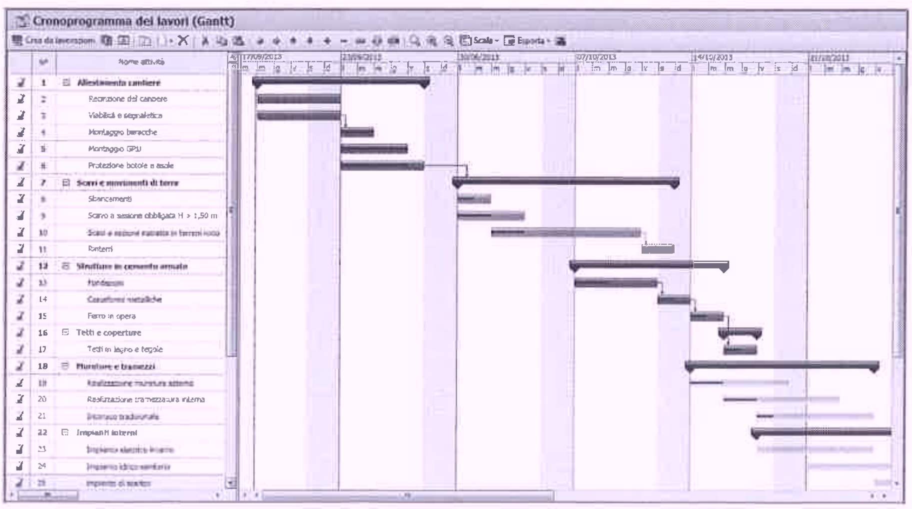


It's proper for each layer

Earthworks total time

Actions 2 and 3

Same methodology for all other actions. It should be underlined that in the case of the construction of the embankment the GANTT chart is evaluated for each sub-layer



Now it is possible to evaluate the total time to finish the embankment

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Construction of Roads, Railways and Airports (01RVMMX)

EARTHWORKS
Soil stabilization

BASICS

When available soil materal is unsuitable, different options are possible.

→ digging + transport

1. SUBSTITUTION WITH QUARRIED MATERIAL (most obvious)

AGAINST
- HIGH COSTS (disposal of old material and transportation of new one)
- ENVIRONMENTAL PROBLEMS (opening of borrow quarries, disposal of unsuitable soil)

⇒ employed of material which is suitable

2. STABILIZATION (alternative method)

modify soil

⇓

→ or series of process

Process which entails the addition of materials (binders or aggregate fractions) in order to enhance physical and mechanical properties of soil

13/11/2017

CHEMICAL STABILIZATION
GENERAL OVERVIEW

} which range for lime and cement + tools

STRUMENTI / MACCHINE

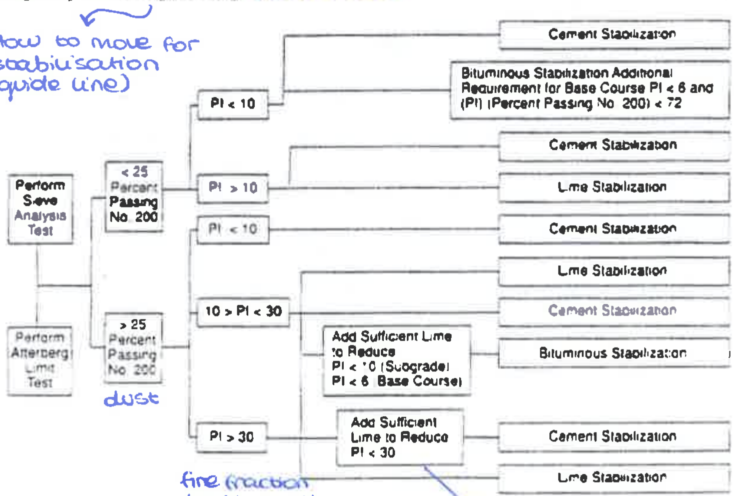
The choice of additive type and dosage depends upon several factors, such as:

- Nature and characteristics of soil
- Purpose of stabilization (improvement of properties in the short and/or long term) why do we want to modify the soil?
- Final requirements of the stabilized mixture (strength, stiffness)
  ↳ statement of design process
- Cost and environmental factors

CHEMICAL STABILIZATION

Criteria for selection of stabilization type
(Dept. Of the Army, 1983) (rather old) => flow chart

How to move for stabilisation (guide line)



dust

fine fraction plastic or not

} Lime stabilization is not very good if soil is not sufficiently plastic

} First stabilization with lime and then with cement

↳ general view of what happens

→ addition of lime reduce plasticity

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LIME TREATMENT = f (Time)

SHORT TERM effects

- Variation of natural water content (not because we add particles, but also because of chemical reactions)
- Variation of soil characteristics
  - ➢ SIZE DISTRIBUTION
  - ➢ PLASTICITY
  - ➢ COMPACTABILITY
  - ➢ MECHANICAL PROPERTIES

LONG TERM effects

- Increase of mechanical properties as a result of pozzolanic effects of lime

they require time to be completed (pozzolanic reactions)

LIME TREATMENT

Short term reaction mechanisms

- ***DRYING*** (adding solid material + chemical bonding)
  due to chemical bonding of water and to evaporation caused by temperature increase generated by a strongly exothermic reaction (**quick lime**) ~ production of heat

  $$CaO + H_2O = Ca(OH)_2 + 64900\ J/mole$$ (we consume part of the water)

  after 2h: $\Delta w\% = 1$ or 1.5% for each 1% of added CaO.

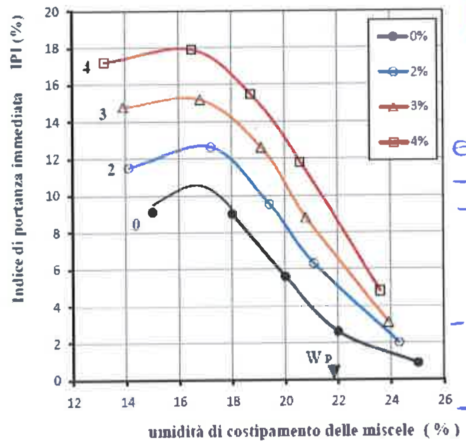
- ***FLOCCULATION*** (single particles lump together to form bigger ones)
  due to the exchange of free Ca^{++} ions in solution with cations Na^+, K^+, etc., with the subsequent formation, in the first hours of treatment, of bonds among the dispersed clay particles which are agglomerated, thus easing mixing and compaction operations.
  ↳ secondary bonding reactions
  ↳ electro chemical effects

⟹ variation of its aspect because of flocculation (transformed even for size distribution)

LIME TREATMENT

SHORT TERM effects on mixtures

- Improvement of **mechanical properties**



↳ just a penetration test
↳ with no surcharge ? of sample and immediate after bearing

Immediate bearing index (CBR)
Indice di Portanza Immediata IPI
(EN 13286-47)

GENERAL OBSERVATIONS:
- bell shape curve
- dependency of line which we have for each quantity of lime
- reduction of density increases mechanical properties
- reduction of maximum values related to dosage

LIME TREATMENT

LONG TERMS reaction mechanisms ↳ provides strenght and stiffness
POZZOLANIC REACTION (same as in cement)
Typical reactions between lime and clayey soil are the following:

$$Ca(OH)_2 = Ca^{++} + 2[OH]^-$$

$$Ca^{++} + 2[OH]^- + SiO_2 \text{ (clay silica)} = CxSyHz$$

$$Ca^{++} + 2[OH]^- + Al_2O_3 \text{ (clay allumina)} = Cx'Ay'Hz'$$

] Hydrated calcium silicates and aluminates

in which indexes x,y,z and x',y',z' depend upon clay type: montmorillonite (very reactive), caolinite (mean reactivity) or illite (low reactivity).
↳ it's better having an idea of reactivity before tests.

PARAMETERS WHICH INFLUENCE LIME ACTION (faster)
- **Specific surface** (high) both of lime and soil
- **Carbonatation** : $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$ (avoid exposition to air) → not beneficial (we'd like to have hydrated calcium silicates and alluminates so we need $Ca(OH)_2$) ↳ protection
- **Duration of treatment**
- **Compaction mode**
- **Water content**
- **Temperature** (reactions are accelerated by 4 time passing from 10 to 20 °C and by 10 times passing from 20 to 40 °C),
- **Organic matter** (can retard or inhibit reactions)
  ↳ low content it's better (even in concrete)

LIME TREATMENT

Design of lime treatment – *Use in embankments*

SHORT TERM REQUISITES (for laying and compaction)

↳ ***Soil Improved by Lime*** (not completely stabilized because we don't consider long term effects)

Immediate bearing index – IPI (*evaluated after not more than 90 minutes after compaction*)

Immediate bearing index	Category *
≥ 5	IPI_5
≥ 7	IPI_7
≥ 10	IPI_{10}
≥ 15	IPI_{15}
≥ 20	IPI_{20}
≥ 25	IPI_{25}
Declared value	IPI_{DV}

reference value for mixed design

* The category has to be established as part of design

LIME TREATMENT

Design of lime treatment – *Use in embankments*

SHORT TERM REQUISITES (for laying and compaction)

↳ ***Soil Improved by Lime***

Compaction degree
↳ minimum level of density

The ratio in % of the in situ dry density to the Proctor (see NOTE) dry density determined in accordance with EN 13286-2	Category *
≥ 95	DC_{95}
≥ 97	DC_{97}
Declared value	DC_{DV}

European standards

LIME TREATMENT

Design of lime treatment – *Use in subgrades*

SHORT TERM REQUISITES

wider range of mechanical properties

CBR index (test carried out after curing followed by saturation)

CBR requirement after 4 days soaking (or other longer specified period)	Class *
≥ 15	CBR_{15}
≥ 20 and not less than the immediate bearing index	CBR_{20}
≥ 30 and not less than the immediate bearing index	CBR_{30}
≥ 40 and not less than the immediate bearing index	CBR_{40}
≥ 50 and not less than the immediate bearing index	CBR_{50}
Declared value (but not less than 15)	CBR_{DV}

minimum value of compressive strength and value after real CBR test

Compression strength (test carried out after curing followed by saturation)

Compressive strength	Class *
≥ 0.2 MPa	R_c 0,2
≥ 0.5 MPa	R_c 0,5
≥ 1.0 MPa	R_c 1,0
Other declared value but not less than 0.2 MPa	R_c DV

⇒ UP TO THE DESIGNER

LIME TREATMENT

Design of lime treatment – *Use in subgrades*

SHORT TERM REQUISITES

Stability to water (x: n° of days of curing + 14 days immersed in water)

$$I_m = \boxed{\frac{R(x+14i)}{R(x+14)} \geq 0{,}8}$$

i = immersione

Stability to freeze/thaw (very aggressive process)

to saturated sample

$$I_g = \boxed{\frac{R(x+1i+13g)}{R(x+14i)} \geq 0{,}8}$$

g = gelo

x = days of curing in controlled conditions
i = immersion in water
g = conditioning in freeze conditions

LIME TREATMENT

2. Spreading of lime and water

- *"DRY"* method (**in the absence of wind**); distribution of bags on the surface to be treated according to required dosage (per mq) or by means of specific spreading equipment; distribution not in excess of surface which can be treated in 1 day to prevent removal from wind and CARBONATATION;
  not more time than this
- "*WET*" method (**in areas with wind**); preparation of water-lime mixture MIXERS which are in continuous agitation to prevent SEDIMENTATION during storage.
  ↳ we have a slorry already wet, not a dusty material



LIME TREATMENT

3. Mixing and pulverization

A uniform mixing is guaranteed by an adequate *pulverization* of soil in situ. Thus, for highly clayey soils this is done in two steps:

- First addition of lime (and water, if needed), start of pluvirization;
  ↳ formation of lumps starts
- After 24 - 48 hours: second addition of lime which can be homogenized until clay lumps are reduced to sandy form with at least 60% passing sieve n. 4 ASTM.



we can consider the particles (more easy to compact)

CEMENT STABILIZATION
↳ more simple

→ reaction similar to the ones which occur in concrete

By contrast to lime, cement generates a real setting phenomenon with a relevant increase of mechanical properties.

FACTORS WHICH INFLUENCE CHARACTERISTICS OF MIXTURES

1. Soil type
2. Cement content
3. Water content
4. Correct development of setting and curing
   ↳ protect by impermeable layers

It is possible to stabilize with cement a wide range of soils.

Exclusion:

- VERY PLASTIC SOILS (PI >15)
- SOILS CONTAINING SUPHATES AND E ORGANIC MATTER

CEMENT STABILIZATION

Mix design (UNI EN 14227-10:2006)

- Cement dosage
- Water content

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R TRUCK

For railways we have differences

ROAD AND AIRPORT PAVEMENTS

Types and performance

BASICS

Pavement: upper part of the road prism, generally built in several layers, directly affected by vehicle loadings and environmental effects.
↳ that's why we choose some materials and not others

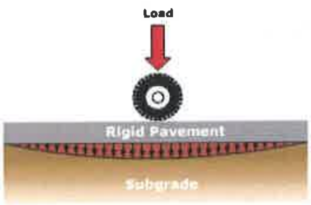
REQUISITES

- ❑ STRUCTURAL
  - load spreading capacity of vehicle loads to subgrade; (limiting stresses) only after some periods of time or in certain conditions → after n° of vehicle passes
  - resistance to structural distress phenomena;
- ❑ FUNCTIONAL
  - evenness and skid resistance of the surface (comfort and safety)
    ↳ rubber and pavements (interaction)

14/11/2017

TYPES

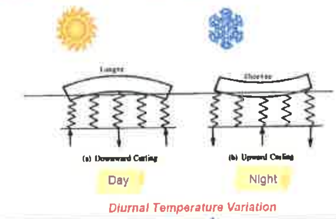
RIGID



⇒ more durable, complicated and expensive

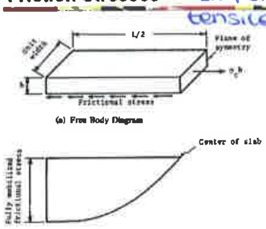
- High stiffness of concrete slab
- Discontinuities (joints) → need to be designed
- Stresses caused by thermal gradients
- Stresses caused by friction due to thermal and hygrothermic effects (better for fire resistance)

Temperature Curling → curvature of pavement due to temperature



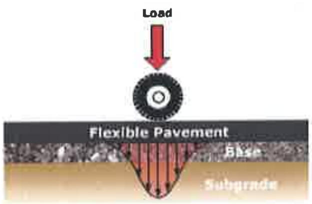
Taking to account on behaviour

Friction Stresses it's compressed because of temperature, it reacts with tensile stress and it can be cracked



TYPES

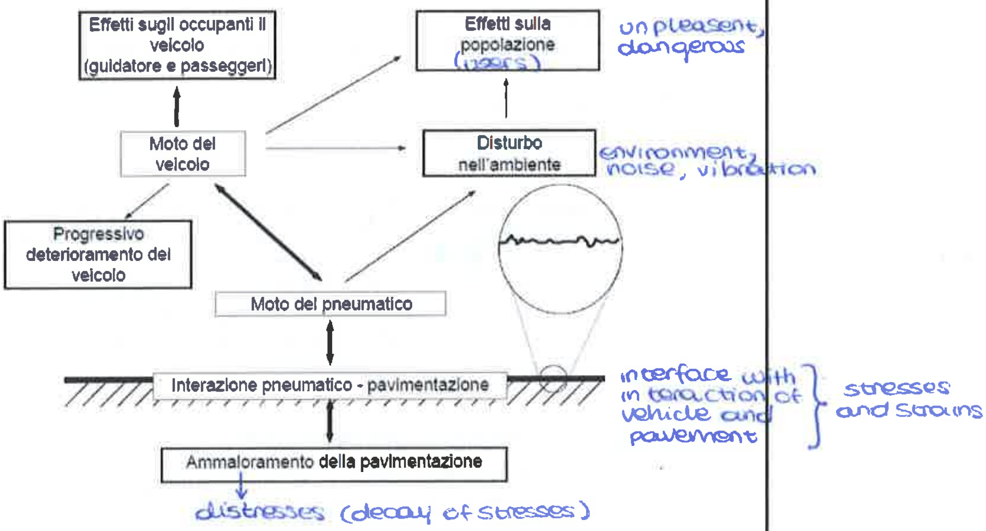
FLEXIBLE



- Lower stiffness of bitumen-bound layers
- Visco-elastic behaviour
- Mechanical properties affected by temperature
- Construction and maintenance simplicity

⇒ very diffuse (easier, cheaper)
↳ in Italy are the standards, rigid pavements are used on the parking of airports or particular motorways.

PERFORMANCE



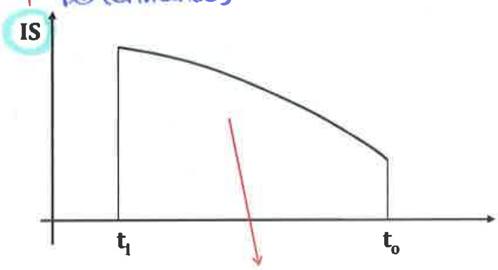
PERFORMANCE

↳ property and how it changes during time

Performance: capability of a pavement to maintain in time one or more characteristics, each of which can be physically measured and expressed by a state indicator (IS)

RESPONSE IN A GIVEN MOMENT

↑ (indicator of performance)



PERFORMANCE INDEX

$$IP = \int_{t_i}^{t_0} IS(t)\,dt$$

how properties change in a period of time (= integral)

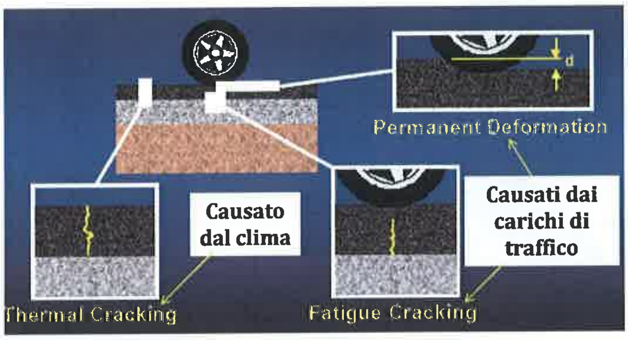
DECAY OF RESPONSE IN TIME AS A RESULT OF TRAFFIC AND ENVIRONMENT

POTHOLE (buca)

DISTRESS PHENOMENA – Flexible pavements

↑ in time
↳ major categories of the stress (NOT the only ones)

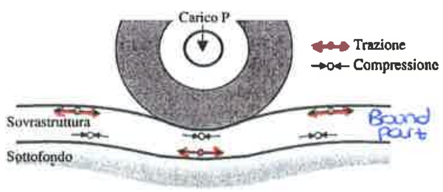
- ❑ Fatigue cracking
- ❑ Rutting (accumulation of permanent deformations)
- ❑ Thermal cracking

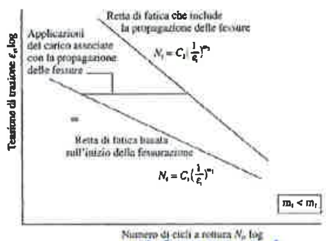


DISTRESS PHENOMENA – Flexible pavements

Fatigue cracking cycle of tensile and compression loads to cracks (important in design)

- Diffused cracking at the surface (alligator cracking)
- Cracks in the bound layers
- Caused by repeated loading





= f (level of tensile strenght in the material)
↳ it's strenght dependent

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DISTRESS PHENOMENA – Rigid pavements
↳ multitude of them is enormous

- ❑ **Cracking**
- ❑ ***Pumping* and joint failure**

DISTRESS PHENOMENA – Rigid pavements

Cracking

- Stresses in excess of tensile strength of concrete (very high stress)
  ↳ it's not ductile
- Fatigue (related to specific points of pavement)

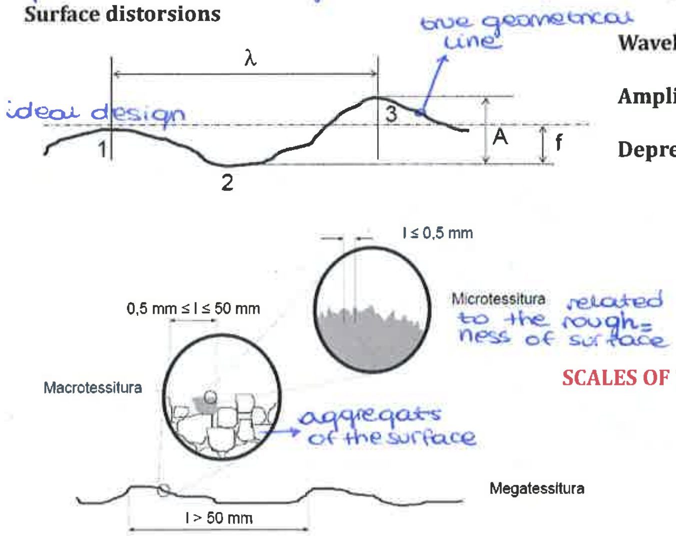
Caused by the combined effects of loading and thermal coactions

LONGITUDINAL CRACKING — TRANSVERSE CRACKING — CORNER CRACKING

SURFACE CHARACTERISTICS

→ different wavelength (random shape so not perfectly sinusoidal)

Surface distorsions



Wavelength λ

Amplitude A

Depression f

FOURIER ANALYSIS: every function can be described as a sum of sinusoidal functions

SCALES OF TEXTURE

SURFACE CHARACTERISTICS

MICROTEXTURE
(mineralogic choose)

- ❑ Distorsions with a characteristic wavelength < 0,5 mm
- ❑ Related to the roughness of aggregates
- ❑ Influences skid resistance in wet conditions (low speed)

MACROTEXTURE
(mix design so soil distribution)

- ❑ Distorsions with a characteristic wavelength comprised between 0,5 mm and 50 mm
- ❑ Related to size distribution of exposed aggregates
- ❑ Influences skid resistance in wet conditions (high speed)

SURFACE CHARACTERISTICS

MEGATEXTURE – ROUGHNESS (threshold in technical specifications)

- Megatexture → 50 mm < λ < 50 cm
- Roughness → λ > 50 cm

we don't want to have them!

↳ effects on vibration of vehicles (it's excited)

❑ Caused by: traffic, inappropriate materials, construction defects

❑Effects: skid resistance (loss of contact), water ponding (acquaplaning), vehicle control, driving comfort, vehicle damage, noise

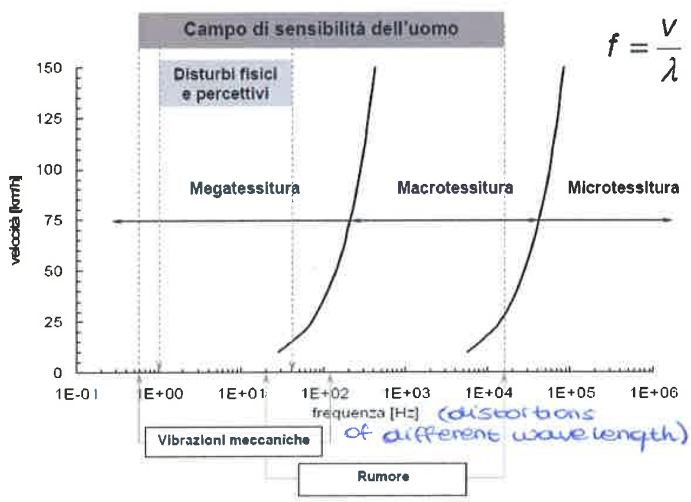
→ vehicle bounces

↳ with bumps (dossi)

no control of vehicle because of a water film

SURFACE CHARACTERISTICS

Perception ranges



$$f = \frac{v}{\lambda}$$

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ROAD AND AIRPORT PAVEMENTS

Aggregates then bituminous mixture and then other parts.

importance to properties of material is very relevant (engineer often judges materials)

BASICS

different sizes

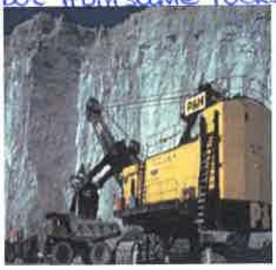
Aggregates are particles of mineral origin which are widely used in the costruction of road and airport pavements, both in unbound form and in combination with various types of binders.

Examples:

- granular mixtures (foundation - unbound)
- cement stabilized mixtures (binder)
- concrete
- bituminous mixtures
- surface treatments (to restore soil resistance)

PRODUCTION CYCLE

we can obtain different materials through different processes but from same rocks.



EXTRACTION

⇩

TRANSPORT

⇩

MILLING

⇩

STORAGE

QUALIFICATION

→ assessment of the quality of materials

The characterization and selection process of aggregates requires the evaluation of several properties:

Two families (+ one)

❑ **GEOMETRIC**

- Particle size and size distribution
- Shape

❑ **PHYSICAL-MECHANICAL**

- Density and absorption
- Resistance to fragmentation
- Resistance to wear
- Resistance to polishing
- Resistance to freeze/thaw

❑ **QUALITY OF FINES** (Miscellaneous)

- Sand equivalent

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GEOMETRIC PROPERTIES - Particle size distribution

↳ both bound or unbound

Particle size distribution affects: → grading envelopes or ranges

- Achievable degree of compaction of the mixture
- Workability
- Mechanical properties

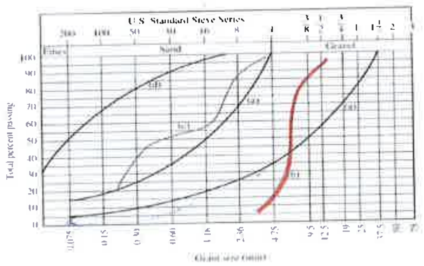
$$P(d)[\%] = 100 \cdot \left(\frac{d}{D}\right)^n \longrightarrow$$ Maximum density curve according to Fuller (**n = 0,5**)

↳ the Fuller's size distribution is used for concrete

For bituminous mixtures reference is made to **n = 0,45** (FHWA)

GEOMETRIC PROPERTIES - Particle size distribution

Graphical representation



a: maximum density curve;

b: monogranular distribution; in a narrow range (from 100% to 0%)

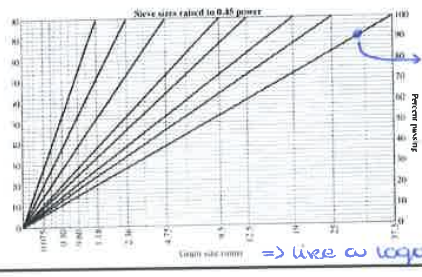
c: gap-graded distribution;

d: open

CURVE SHAPE FACTORS

$$F = \frac{D_{P1}}{D_{P2}} \left(es. \frac{D_{70}}{D_{30}} \right)$$

↳ percentage of passing (it's a number)



FHWA representation

↳ line of maximum density

⇒ like a logarithmic scale but elevating to 0,45

GEOMETRIC PROPERTIES - Shape

→ truly flat: they go through the bars

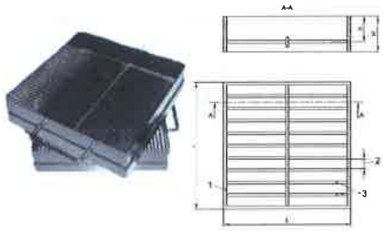
Flakiness index (UNI EN 933-3:2004)

$$FI = 100 \cdot \frac{M_2}{M_1}$$

M_2 = sum of the masses of particles passing the various sieves

M_1 = sum of the masses of all size fractions

BAR SIEVES



they are narrow

Classi granulometriche d_i/D_i mm	Larghezza dell'apertura nello staccio a barre mm
63/80	40 ± 0,5
50/63	31,5 ± 0,5
40/50	25 ± 0,4
31,5/40	20 ± 0,4
25/31,5	16 ± 0,4
20/25	12,5 ± 0,4
16/20	10 ± 0,2
12,5/16	8 ± 0,2
10/12,5	6,3 ± 0,2
8/10	5 ± 0,2
6,3/8	4 ± 0,15
5/6,3	3,15 ± 0,15
4/5	2,5 ± 0,15

The aggregates has to be divided in size fractions each of which needs to be sieved through the corresponding bar sieve

→ more physical than geometric

GEOMETRIC PROPERTIES - Density

surface porosity accessible to water

Dry aggregate –
M_S = dry mass; V_N = Net volume (excluding porosity)

Saturated surface dry aggregate –
M_{SSD} = saturated surface dry mass (comprises dry mass plus absorbed water);
V_B = Effective volume (comprises net volume and surface porosity permeable to water)

soaking material and then pulling with paper → saturated, but dry on surface

$$\rho\, MV_A = \frac{M_S}{V_N} \quad \text{Apparent density}$$

massa volumica

$$MV_B = \frac{M_S}{V_B} \quad \text{Oven-dried density (effective)}$$

→ (V_N + V of the pours (may be full of water)) This volume is bigger than the VN and it's true

it's the true occupied volume (4)

$$MV_{SSD} = \frac{M_{SSD}}{V_B} \quad \text{Saturated surface dry density}$$

it's the way to pass from mass (easy to measure) to volume (world is made of it)

$$A[\%] = 100 \cdot \frac{M_{SSD} - M_S}{M_S} \quad \text{Percent absorption}$$

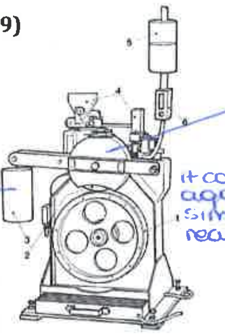
ROUGHNESS (which has to be sufficient and has to be mantained in time) ~ subjected to consume

PHYSICAL-MECHANICAL PROPERTIES - Res. to polishing

1) Some materials even if are consumed, have the roughness which remains the same
2) polish : roughness decreases with consuming

Polished stone value test (UNI EN 1097-8:1999)

The aggregate to be characterized is used to prepare 4 specimens with particles comprised between 6,3 e 10 mm. The same procedure is used to prepare 2 specimens (moulds) with a standard reference aggregate



rubber wheel

weight

it consumes aggregates simulating real process

we want to produce polishing effect

Curved moulds.

Aggregates are «glued» on a support made of cement and resin.

to keep aggregates in position

covered by these two specimens

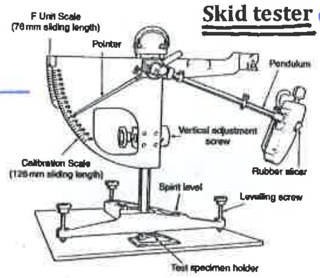
The 14 specimens are inserted in a wheel which rotates with the concurring loading of a rubber wheel:

- 3 hours: coarse grained abrasive + water
- 3 hours: fine grained abrasive + water

PHYSICAL-MECHANICAL PROPERTIES - Res. to polishing

Polished stone value test (UNI EN 1097-8:1999)

after oscillation the pointer moves along the scale according the movement of the pendulum



Skid tester (pendulum) → it slides upon the specimen → we find some friction → wet condition

it changes its speed → a lot of energy is dissipated! energy if it's abrasive

Polished stone value
it's empirical

$$PSV = S + (52{,}5) - C$$

S = average of the values obtained on the material under characterization

C = average of the values obtained on the reference material

The test yields a parameter (BPN) which is a measure of the energy dissipated when a pendulum, with a rubber slider at its extremity, slides over a surface.

TEST CONDITIONS

- Wet surface;
- Initial pendulum oscillation with no registration of results;
- 5 oscillations with measurement of BPN (wetting the surface each time) → British pendulum number
- RESULT: AVERAGE VALUE OF THE LAST THREE OSCILLATIONS

⟹ micro texture is important and has to be mantained in time because macro texture changes with size distribution but micro ones is always fixed (it depends on mineralogy)

CE MARKING

Harmonized European standards

UNI EN 13043:2004 – aggregates for bituminous mixtures and surface treatments

UNI EN 13242:2004 – aggregates for unbound materials or cement-bound,

UNI EN 12620:2003 - aggregates for concrete.

⇩

They define the general properties for aggregates as a function of the intended use

some are mandatory some are optional

For each characteristic a quality category is established (e.g. LA)

Coefficiente Los Angeles	Categoria LA
≤15	LA_{15}
≤20	LA_{20}
≤25	LA_{25}
≤30	LA_{30}
≤40	LA_{40}
≤50	LA_{50}
>50	$LA_{Dichiarato}$
Nessun requisito	LA_{NR}

CE MARKING

- Per **"Norme armonizzate"** s'intendono le **specifiche tecniche** predisposte dal CEN su **Mandato della Commissione** conformemente alla direttiva 83/189/CEE a seguito di un parere favorevole formulato dal comitato tecnico permanente delle costruzioni.
- Gli Stati Membri presumono idonei al loro impiego **i prodotti** che consentono alle opere in cui sono utilizzati di **soddisfare i requisiti essenziali e che recano il marchio CE.**
- **Il Marchio CE attesta che un prodotto è conforme** alle relative norme nazionali in cui sono state trasposte le norme armonizzate.
- È compito del **fabbricante** o al suo mandatario **assumere le responsabilità di apporre il marchio CE** sul prodotto, su un'etichetta apposta sul prodotto, sull'imballaggio o sui documenti commerciali di accompagnamento

Il **marchio CE** garantisce che i prodotti da costruzione marcati:

- soddisfano i requisiti in tema di salute e sicurezza ed i requisiti essenziali delle direttive di prodotto
- sono stati sottoposti alle prove ed alle verifiche previste dalle specifiche tecniche

Abilita all'immissione sul mercato

CE

DICHIARAZIONE DI CONFORMITÀ

La dichiarazione deve contenere almeno

a) Il nome e l'indirizzo del produttore che l'ha redatta;
b) La descrizione del prodotto (Tipo, identificazione, uso, denominazione)
c) Copia delle informazioni che accompagnano la marcatura CE)
d) La dichiarazione di conformità alle norme tecniche;
e) Le condizioni particolari di utilizzo del prodotto
f) La firma, il nome e la funzione della persona autorizzata a firmare a nome del fornitore

POLITECNICO DI TORINO
Master Course
in Civil Engineering
2017-18

Construction of Roads, Railways and Airports (01RVMMX)

ROAD AND AIRPORT PAVEMENTS

Bituminous binders

BASICS

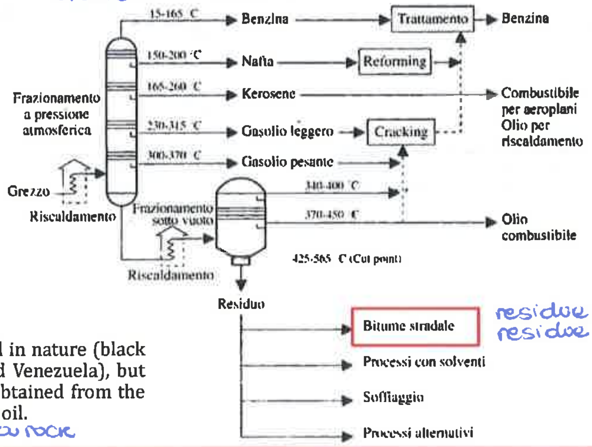
RICHIAMI

BITUMEN - Definition

Mixture of paraffinic and aromatic hydrocarbons with high molecular weight soluble in carbon sulphur CS_2. (= commercial definition)

GENERAL SCHEME

fractionation of material (cherazin)



residue of residue → it's the result of recombine of different material

BITUMEN - Origin

Bitumen can be found in nature (black lakes in Bermuda and Venezuela), but nowadays is mainly obtained from the fractionation of crude oil.

→ extracted as a rock

→ it's not pure so we use additive to make respect L of sandards

BASICS

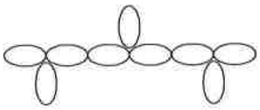
MODIFIED BITUMEN / binders

Obtained from conventional bitumen by means of the addition of polymers, which alter the chemical and physical properties (improve)

POLYMERS (PMB : polymers modified bitumen)
↳ more expensive
Synthesis organic materials, constituted by molecules which have a high number of atoms bonded with covalent bonds.

→ high molecular weight (carbon and hydrogen)
→ produced by industries (organic, not natural)
Polymer = combination of several molecules, known as <u>monomers</u>


Linear omopolymer


Branched omopolymer

OMOPOLYMER → constituted by monomers of the same type

COPOLYMERO → constituted by two or more types of monomers


Random copolymer
(two or more type of omopolymers random arranged)


Block copolymer
(specific arrangement)

BASICS

MODIFIED BITUMEN
↳ wide range of types

Main polmers used as modifiers

THERMOPLASTIC ELASTOMERS (RUBBER) → elastic → not stiff → repeated loads don't lead to fracture

most used ←	**Styrene-Butadiene-Styrene**	**SBS**
	Styrene-Isoprene-Styrene	**SIS**
	Styrene-Butadiene	**SB**
	Copolymer Random	**SBR**

→ **Elastomers** = increase of elasticity

THERMOPLASTIC PLASTOMERS (PLASTIC) → stiff → non elastic → increase stiffness of bitumen

Ethylene-Vinyl-Acetate	**EVA**
Ethylene-Metyl-Acrylate	**EMA**
Plyisobutylene	**PIB**

→ **Plastomers** = stiffening

BASICS

BITUMEN MODIFIED WITH SBS

Modification reaction

Mixing of bitumen and polymer in the fluid state (high T) → temperature

1) Butadienic chains absorb the maltenic fraction with volume increase (beneficial)
↳ part of the oily fraction is absorbed

2) As temperature decreases, the elastomeric macromolecules tend to form a three-dimensional network within the bituminous matrix

Degree of modification = 3-6% of polymer b.w. of bitumen
↳ great modification with a small quantity of polymers.

⇒ NEW BINDER, changes properties. It doesn't change in this way if we add only pellets.

BASICS

BITUMEN MODIFIED WITH SBS

ADVANTAGES

1) Increase of stiffness and elasticity at high temperatures
2) Decrease of stiffness and elasticity at low temperatures → low temperature rubber acts as a rigid component
   → Improved fatigue resistance
   → Improved resistance to permanent deformation
   → Improved resistance to thermal cracking
3) Improved adesion to aggregates
4) Improved resistance to ageing (bitumen in time changes properties due to UV, temperature, ecc.)
   → Improved durability

DISADVANTAGES

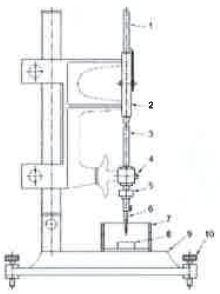
1) Increase of viscosity at mixing and compaction temperatures
   → Lower workability (higher compaction temperature)

EMPIRICAL CLASSIFICATION SYSTEM

RICHIAMI

↳ kind of empirical tests

PENETRATION TEST – EN 1426



MANUALE

1: alberino; 2: quadrante di regolazione; 3: ancoraggio dell'ago; 4: assemblaggio di rilascio; 5: massa di 50 g; 6: ago e ghiera; 7: capsula di trasporto a fondo piatto; 8: contenitore del campione di prova; 9: basamento; 10: vite di regolazione del livello

AUTOMATICO

Test temperature = 25°C
↳ conventional

Mass on the needle = 100 g

Penetration time = 5 s

⇩

Penetration in dmm (hardness of bitumen)

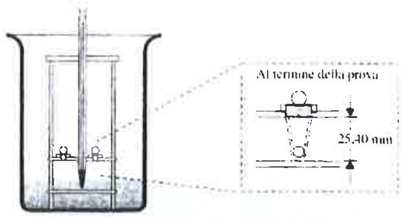
Bitumen is classified in penetration grades (e.g. 50/70, 80/100)

EMPIRICAL CLASSIFICATION SYSTEM

RICHIAMI

↳ temperature gradient in time

SOFTENING POINT TEST (Ring & Ball method) – EN 1427



Initial test temperature : 5°C

Temperature gradient : 5°C / 60s

Load: steel spheres 3,5 g

Loading time: until contact between bitumen and lower strip

Result : softening point temperature [°C] it's the temperature at which bitumen changes behaviour (it's empirical)
no direct correspondence between this temperature and the one in which pavement has a critical behaviour because it's a test for a sample and it's empirical

21/11/2017

→ Tests can't be correctly used for modified bitumen (these are different)

EMPIRICAL CLASSIFICATION SYSTEM

→ historical reasons but nowadays we use different tests

CNR SPECIFICATIONS (B.U. n.24/71)

quick tests

Caratteristiche		Bitumi semisolidi per usi stradali				
		B 40/50	B 50/70	B 80/100	B 130/150	B 180/220
Penetrazione a 25 °C	dmm	40–50	50–70	80–100	130–150	180–220
Punto di rammollimento (palla e anello)	°C	51–60	47–56	44–49	40–45	35–42
Punto di rottura (Fraass), massimo .	°C	—6	—7	—10	—12	—14
Duttilità a 25 °C, minima	cm	70	80	100	100	100
Solubilità in solventi organici, minima	%	99	99	99	99	99
Perdita per riscaldamento (volatilità):						
a 163 °C, massima	%	—	—	0,5	1	1
a 200 °C, massima	%	0,5	0,5	—	—	—
Penetrazione a 25 °C del residuo della prova di volatilità: valore espresso in percentuale di quello del bitume originario, minimo	%	60	60	60	60	60
Punto di rottura del residuo della prova di volatilità, massimo . .	°C	—4	—5	—7	—9	—11
Contenuto di paraffina, massimo .	%	2,5	2,5	2,5	2,5	2,5
Densità a 25/25 °C		1,00–1,10	1,00–1,10	1,00–1,07	1,00–1,07	1,00–1,07

Nella presente norma viene applicato il Sistema internazionale di unità (SI) – ved. Norma CNR-UNI 10003-74. In particolare, lo stesso numero che esprime il peso nel Sistema Tecnico, prima in uso, esprime la massa nel Sistema SI.

→ to check if it's bitumen or not

→ limit loss of volatility components

→ after volatility test penetration and softenig point

waxes (bad behaviour)

EMPIRICAL CLASSIFICATION SYSTEM

C.E.N. SPECIFICATIONS (EN 12591:1999)

Specifiche C.E.N. per bitumi stradali
Aggiornamento a Dicembre '99 (estratto dalla norma EN 12591/1999)

Grado	metodo E.N.	corrisp C.N.R.	unità di misura		20/30	30/45	35/50	40/60	50/70	70/100	100/150	160/220
Caratt. fondamentali												
Penetrazione @ 25°C	EN 1426	24/71	mm/10		20-30	30-45	35-50	40-60	50-70	70-100	100-150	160-220
Rammollimento	EN 1427	35/73	°C		55-63	52-60	50-58	48-56	46-54	43-51	39-47	35-43
Punto di infiammabilità	EN 22592 (1)	72/79	°C	min	240	240	240	230	230	230	230	220
Solubilità	EN 12592	48/75	%	min	99	99	99	99	99	99	99	99
Resistenza all'invecchiam.	EN 12607-1	54/77										
- Variazione di peso	EN 12607-1	54/77	%	max	0.5	0.5	0.5	0.5	0.5	0.8	0.8	1.0
- Penetrazione residua	EN 1426	24/71	%	min	55	53	53	50	50	46	43	37
- Rammollimento dopo invecchiamento	EN 1427	35/73	°C	min	57	54	52	49	48	45	41	37
Caratt. Nazionali (2)												
Punto di rottura Fraass	EN 12593	43/74	°C	max	-5	-5	-5	-7	-8	-10	-12	-15
Resistenza all'invecchiam.												
- Incremento massimo del rammollimento (3)	EN 1427	35/73	°C	max	10	11	11	11	11	11	12	12

EMPIRICAL CLASSIFICATION SYSTEM

Traditional system

ADVANTAGES

- Consolidated use (lot of experience)
- Acceptable reliability for traditional/standard materials (different materials, but also different production process)
- Speed of testing and possibility of usage in field laboratories
- Low cost of testing equipment

LIMITATIONS

- Empirical tests with measurement of non-fundamental properties (weakness)
- Prescriptive approach rather than performance-based (clear link of performance lacks)
- Not adequate for innovative materials or of different type
  - Variability of crude oil sources
  - Evolution of refining processes
  - Enhanced materials (modified binders, synthetic, etc.) + bio binders → producted by agricultural processes

BINDER RHEOLOGY

OTHER TOOLS

RHEOLOGY (different science)

Studies phenomena related to flow and deformation of complex materials which do not follow simple behavioural laws

↓

VISCO-ELASTIC MATERIALS

Elastic and viscous components

Bitumen is visco-elastic

Its behaviour depends upon:

- Temperature (termal plastic material)
- Loading time (frequency) – any visco-elastic material depends on how fast load is and on time in general
- Ageing (properties change in time) – uv radiation, oxidation, environmental changes.

IMPORTANT

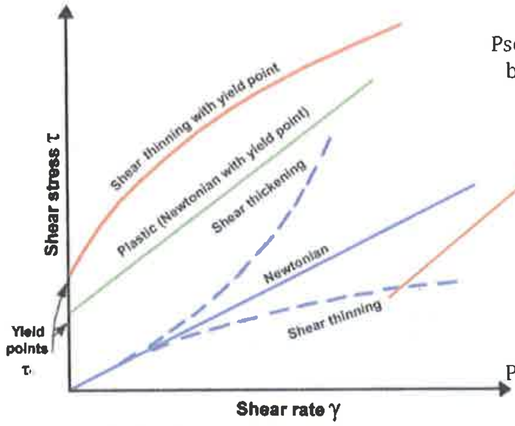
Visco-elastic behaviour of bitumen affects its performance in pavements

=) measurements linked to real visco-elastic behaviour

it controls bitumen in fields (=) it's our need!)

BINDER RHEOLOGY

LINEAR AND NON LINEAR VISCOSITY



Bitumen behaviour varies from Newtonian to non-Newtonian as temperature decreases

Pseudo-plastic behaviour (typical for bitumen in non linear conditions)

$$\frac{\eta_o-\eta}{\eta-\eta_\infty}=\left(k\frac{d\gamma}{dt}\right)^m$$

CROSS – MODEL

Per $\eta \ll \eta_0$ e $\eta \gg \eta_\infty$

$$\eta=\frac{\eta_o}{(k\cdot d\gamma/dt)^m}=K\left(\frac{d\gamma}{dt}\right)^n$$

POWER-LAW MODEL (OSTWALD)

increase speeding viscosity decrease (shear thinning) or viceversa with shear thickening material

⇒ viscous behaviour for bitumen when we mix it with aggregates or when we compact layers.
↳ flow behaviour for bitumen

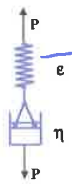
BINDER RHEOLOGY

ANALOGICAL MODELS

Linear visco-elasticity

same stress will applied in equal way to the 2 component, but the total strain is given by the sum

Maxwell model



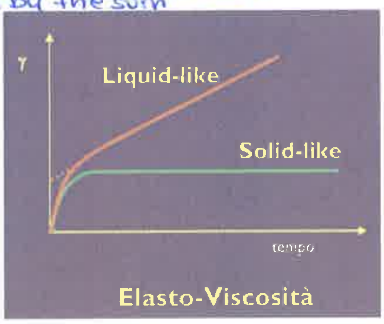
→ $\tau = G\gamma$

$$\left(\frac{d\gamma}{dt}\right)=\frac{1}{G}\frac{d\tau}{dt}+\frac{\tau}{\eta}$$

→ $\tau = \eta\cdot\dot{\gamma}$

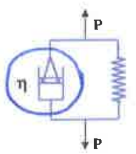
$$\gamma(t)=\left(\frac{1}{G}+\frac{t}{\eta}\right)\cdot\tau$$

$\gamma_{TOT} = \gamma_E + \gamma_V$
$\tau_{TOT} = \tau_E = \tau_V$



Kelvin-Voigt model

dashpot ←



$$\tau=G\cdot\gamma+\eta\frac{d\gamma}{dt}$$

$$\gamma(t)=\gamma_0\left[1-e^{-\frac{t}{\lambda}}\right] \rightarrow \lambda=\frac{\eta}{G}$$ ***Relaxation time***

$\gamma_{TOT} = \gamma_E = \gamma_V$
$\tau_{TOT} = \tau_E + \tau_V$

21/11/2017

BINDER RHEOLOGY

Tests in continuous regime (*creep*)

$\boxed{\tau = \tau_0}$ → we monitor strain

$S(t) = \dfrac{\tau_0}{\gamma(t)}$ *Creep Stiffness* $= f(t)$ not a single value
↳ as elastic material

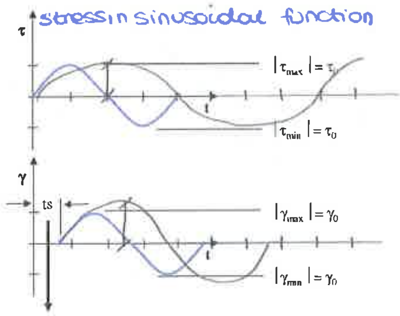
↳ time dependent

$J(t) = \dfrac{\gamma(t)}{\tau_0}$ *Creep Compliance*

BINDER RHEOLOGY

Oscillatory tests

stress in sinusoidal function



$\tau(t) = \tau_0 \cdot sen(\omega t)$

ω: pulsation of sen function or frequency

$\gamma(t) = \gamma_0 \cdot sen(\omega t - \delta)$

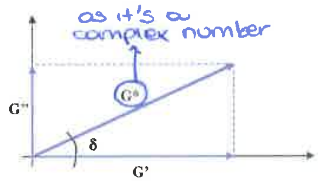
↳ if it's viscoelastic even the responce is oscillatory
↳ but it's out of phase

Out of phase

Complex modulus

$G^* = \dfrac{\tau_0}{\gamma_0}$

as it's a complex number



ELASTIC COMPONENT → even if we can't completely discriminate them.

$G' = G^* \cdot \cos\delta$ → phase angle → measure how much the two curves are out of phase

$G'' = G^* \cdot \sin\delta$

$G^* = \sqrt{G'^2 + G''^2}$

VISCOUS COMPONENT

$\dfrac{\text{max amplitude of stess}}{\text{max amplitude of strain}}$ → not correspondence values → not f(t) or f(ω) → it's not TRUE!!

it seems not to be a function of time and frequency, but it is!

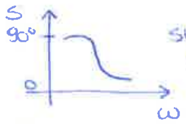
If we change frequency, maintaining amplitude equal, in strain amplitude increases because it has more time to show its behaviour (deformation)

↓ω ↓G* δ↑

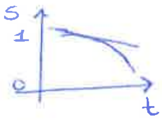
↑ω ↑G* δ↓

=> S(t) ; G(ω) ; δ(ω)

23/11/2017

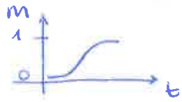


sigmoidal shape



we can consider the slope of the tangent ↳ it's negative } we consider the modulus m

$\left|\frac{d \log S}{d \log t}\right| = m$



the creep rate tents to 0° in the glassy asymptote, but in viscous asymptote tenst to 1 (viscous response)

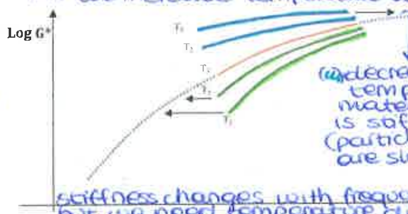
elastic response

each point has a couple of coordinates then if we shift the curve we need to add or subtract the same value for the points of the same lines

BINDER RHEOLOGY

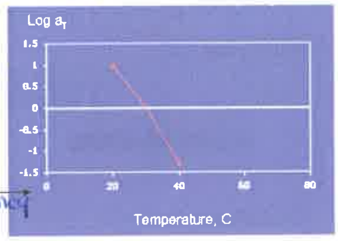
Time-temperature equivalence (superposition) principle

↳ response of binder in a fixed temperature
↳ if we increase temperature with same frequency, complex modulus decreases (ω)



(ω) decreasing temperature material is softer (particles are slower)

stiffness changes with frequency but we need temperature dependency with a(T)
↳ complete description



REDUCED VARIABLES METHOD

$$\omega_r = \omega_s \cdot a(T) \rightarrow \log(\omega_r) = \log(\omega_s) + \log a(T)$$

SHIFT FACTOR

Measured frequency

Reduced frequency

Shift Factors

$$\log \frac{a(T)}{a(T_0)} = \frac{-C_1 \cdot (T - T_0)}{C_2 + T - T_0}$$

Williams – Landel – Ferry

$C_1 = 19$, $C_2 = 92$ (bitumi)

$C_1 = 17{,}44$, $C_2 = 51{,}6$ (polimeri)

$T_0 = T$ $a(T) = 1$

shifted to the left $a(T) < 0$

shifted to the right $a(T) > 0$

SUPERPOSITION EFFECT: effects of frequency and temperature can be summed
↳ the curves (ω) and (ω) are shifted until we obtain only one curve for a REFERENCE TEMPERATURE
↳ at different temperature we can consider the response at different frequencies because we can obtain the curve shifting the curves in different ways according to the reference temperature chosen → we will be able to have a curve for each temperature and frequency

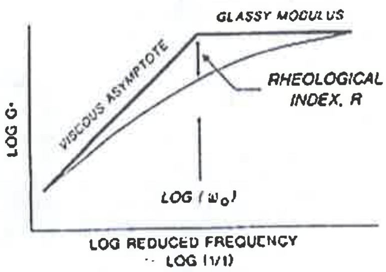
BINDER RHEOLOGY
↳ ANALYTICAL MODEL

Christensen – Anderson analytical model (CA model)

cross over frequency → phase angle (=45°)

$$G^*(\omega) = G_g \left[1 + \left(\frac{\omega_0}{\omega} \right)^{\frac{\log 2}{R}} \right]^{-\frac{R}{\log 2}}$$

glassy modulus



Christensen – Anderson – Marasteanu analytical model (CAM model)

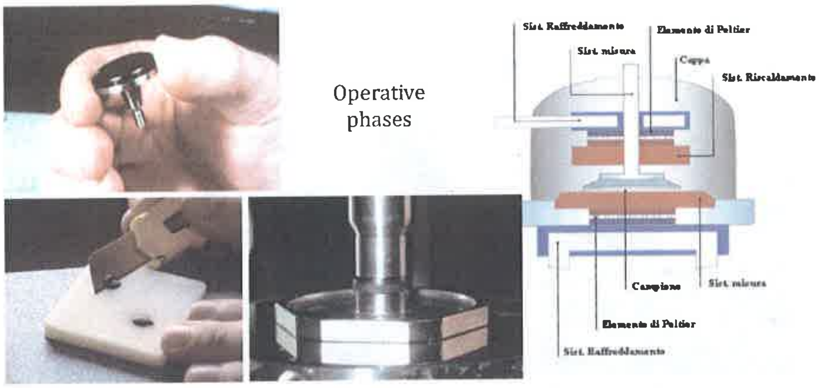
$$G^*(\omega) = G_g \left[1 + \left(\frac{\omega_0}{\omega} \right)^{\frac{\log 2}{R}} \right]^{-\frac{mR}{\log 2}}$$

m = additional parameter very useful for the modelling of modified binders

BINDER RHEOLOGY

Laboratory equipment and test configurations

DSR (*Dynamic Shear Rheometer*)



1) let a drop on the plate (to have the perfect quantity the skill of the operator it's important)
2) prepare with rubber so we can eliminate the excess (precast)

=) Decrease temperature the sample has to be smaller (it becomes stiffer) that's why equipment is so small

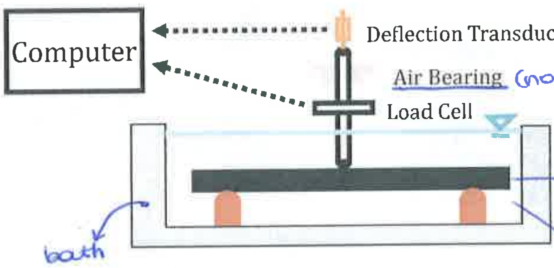
BINDER RHEOLOGY

↳ SUB ZERO TEMPERATURE
↳ elastic / glassy response

Laboratory equipment and test configurations

BENDING CONFIGURATION

Prove di tipo flessionale



(to measure load)

(not mechanic)

prismatic sample → centerly loaded

control deflection for a constant concentrated load

bath

$$S(t)=\frac{P\cdot L^3}{4\cdot b\cdot h^3\cdot \delta(t)} \longrightarrow \text{Stiffness (bending)}$$

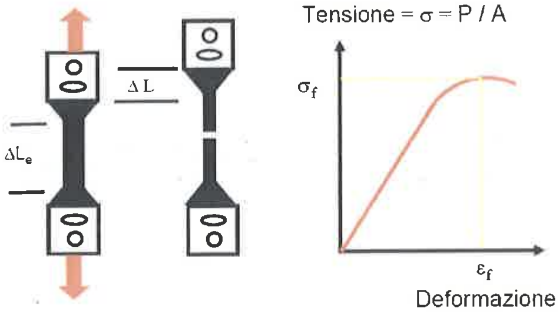
↓ deflection of the center of the beam

BINDER RHEOLOGY

Laboratory equipment and test configurations

DIRECT TENSILE → very low temperature (non ambient)

Prove in configurazione di trazione diretta



Focus on failure condition, non on the stress-strain relationship in time

↳ if material is brittle or ductile

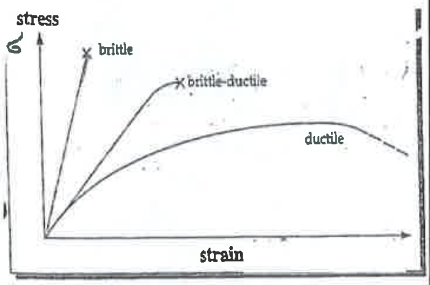
Results depend on the speed of load

↳ very low loading leads to viscous relax → ductile and viceversa

BINDER RHEOLOGY

Laboratory equipment and test configurations

DTT (*Direct Tension Tester*)



BINDER RHEOLOGY

Aging

ciundre

PAV (*Pressure Aging Vessel*)

flat pan

Simulates ageing of bitumen after

7-10 years

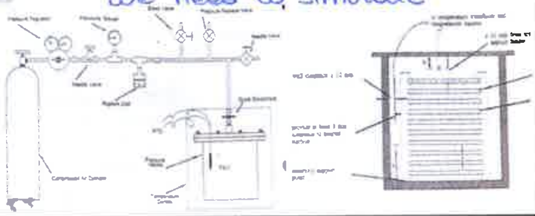
bitumen in pans, pans in the vessel then test.

Duration = 20 hours

Pressure = 300 psi

Temperature = 90, 100, 110°C

depending on the kind of environment we need to simulate



=> Then reological tests

PERFORMANCE-BASED CLASSIFICATION SYSTEM

Basic characteristics of a perfomance-based system

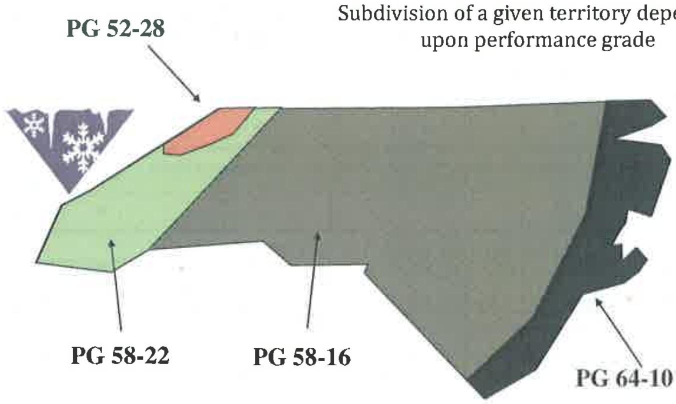
- Based on fundamental properties (not empirical)
  ↳ related to the true stress-strain behaviour
- Experimental measurements carried out in controlled and representative conditions (similar to service conditions - termic and loading)
- Specifications related to main distress phenomena
  ↳ better response changing bitumen

PERFORMANCE-BASED CLASSIFICATION SYSTEM

SUPERPAVE system

Design temperatures

Subdivision of a given territory depending upon performance grade



PERFORMANCE-BASED CLASSIFICATION SYSTEM

SUPERPAVE system

- Rheological tests
  - Measure of fundamental properties related to field performance of mixtures
- Test conditions
  - Representative of srvice temperature and construction phases
- Bitumen ageing
  - Short and long term ageing

21/11/2017

Thermal stress

$\sigma(T) = \alpha \, \Delta T \, S(T)$ → it depend on α, ΔT and S

in elasticity $\sigma = \varepsilon E$ and $\varepsilon = \alpha \Delta T$, but $E = \text{cost}$

1) To have low stress we need low elastic modulus so we have to check the material when it isn't very stiff

2) These stresses are dissipated very quickly in relation with creep stiffness so $m(T)$ has to be high enough ($\geq$ threshold value)
↳ not too much elastic (viscous enough)

PERFORMANCE-BASED CLASSIFICATION SYSTEM

SUPERPAVE system (AASHTO M 320)

PERFORMANCE GRADE	PG 46-			PG 52-							PG 58-					PG 64-					
	34	40	46	10	16	22	28	34	40	46	16	22	28	34	40	10	16	22	28	34	40
Average 7 day Maximum Pavement Design Temperature, °C	<46			<52							<58					<64					
Minimum Pavement Design Temperature, °C	>-34	>-40	>-46	>-10	>-16	>-22	>-28	>-34	>-40	>-46	>-16	>-22	>-28	>-34	>-40	>-10	>-16	>-22	>-28	>-34	>-40
ORIGINAL BINDER																					
Flash Point Temp, T48: Minimum °C	230																				
Viscosity, ASTM D4402: Maximum, 3 Pa·s, Test Temp, °C	135																				
Dynamic Shear, TP5: G*/sinδ, Minimum, 1.00 kPa Test Temp @ 10 rad/s, °C	46			52							58					64					
ROLLING THIN FILM OVEN (T240) OR THIN FILM OVEN RESIDUE (T179)																					
Mass Loss, Maximum, percent	1.00																				
Dynamic Shear, TP5: G*/sinδ, Minimum, 2.20 kPa Test Temp @ 10 rad/s, °C	46			52							58					64					
PRESSURE AGING VESSEL (PAV) RESIDUE (PP1)																					
PAV Aging Temperature, °C	90			90							100					100					
Dynamic Shear, TP5: G*sinδ, Maximum, 5000 kPa Test Temp @ 10 rad/s, °C	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13	31	28	25	22	19	16
Physical Hardening	Report																				
Creep Stiffness, TP1: S, Maximum, 300 MPa, m-value, Minimum, 0.300 Test Temp @ 60s, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30
Direct Tension, TP3: Failure Strain, Minimum, 1.0% Test Temp @ 1.0 mm/min, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30

Performance grade is determined by temperature

$S(t) \leq 300$
$m(t) \geq 0{,}3$

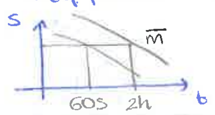
test temperature which is 10 degree above the minimum value of the PG

in long term we have the most severe conditions

⇒ low stresses which decreas very quickly

At first they consider 2 hours of loading time to compute

They prefer using superposition effects



curve is shifting by 10° (even if 10 is not perfecty suitable for all the binders)

DISADVANTAGES
- economical
- different displacement of binder

PERFORMANCE-BASED CLASSIFICATION SYSTEM

SUPERPAVE system (AASHTO M 320)

PERFORMANCE GRADE	PG 46-			PG 52-							PG 58-					PG 64-					
	34	40	46	10	16	22	28	34	40	46	16	22	28	34	40	10	16	22	28	34	40
Average 7 day Maximum Pavement Design Temperature, °C	<46			<52							<58					<64					
Minimum Pavement Design Temperature, °C	>-34	>-40	>-46	>-10	>-16	>-22	>-28	>-34	>-40	>-46	>-16	>-22	>-28	>-34	>-40	>-10	>-16	>-22	>-28	>-34	>-40
ORIGINAL BINDER																					
Flash Point Temp, T48: Minimum °C	230																				
Viscosity, ASTM D4402: Maximum, 3 Pa·s, Test Temp, °C	135																				
Dynamic Shear, TP5: G*/sinδ, Minimum, 1.00 kPa Test Temp @ 10 rad/s, °C	46			52							58					64					
ROLLING THIN FILM OVEN (T240) OR THIN FILM OVEN RESIDUE (T179)																					
Mass Loss, Maximum, percent	1.00																				
Dynamic Shear, TP5: G*/sinδ, Minimum, 2.20 kPa Test Temp @ 10 rad/s, °C	46			52							58					64					
PRESSURE AGING VESSEL (PAV) RESIDUE (PP1)																					
PAV Aging Temperature, °C	90			90							100					100					
Dynamic Shear, TP5: G*sinδ, Maximum, 5000 kPa Test Temp @ 10 rad/s, °C	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13	31	28	25	22	19	16
Physical Hardening	Report																				
Creep Stiffness, TP1: S, Maximum, 300 MPa, m-value, Minimum, 0.300 Test Temp @ 60s, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30
Direct Tension, TP3: Failure Strain, Minimum, 1.0% Test Temp @ 1.0 mm/min, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30

RUTTING

A

B

Each specification is related to a type of distress

FATIGUE

THERMAL STRESS

they don't consider the true ductility of material

optional test: failure strength at least 1% (very low elongation)
If A is satisfied, B is useless because the material is the PG we defined (the range of PG temperature is verified)
If A isn't satisfied material can still be the PG we defined if B is satisfied (in this sense it's optional)

PERFORMANCE-BASED CLASSIFICATION SYSTEM

SUPERPAVE system

ORIGINAL BINDER	
Flash Point Temp, T48: Minimum °C	230
Viscosity, ASTM D4402: Maximum, 3 Pa-s, Test Temp, °C	135

- Flash-point temperature (safety)
- Viscosity
  - Maximum viscosity = 3 Pas at 135 C
  - Used to guarantee sufficient pumpability at typical mixing temperatures

The rotor is immersed in the fluid to be evaluated

Viscosity is given by the ratio between the applied moment and the speed of rotation x calibration constant

BROOKFIELD viscometer

PERFORMANCE-BASED CLASSIFICATION SYSTEM

SUPERPAVE system

Rutting – Control parameter

DSR test

ω= 10 rad/s

Tmax design

Critical conditions
- hgh service temperatures (hot climate)
- traffic (slow)

$G^*/\sin\delta$ on virgin bitumen ≥ 1.00 kPa

$G^*/\sin\delta$ on RTFOT-aged bitumen ≥ 2.20 kPa

PERFORMANCE-BASED CLASSIFICATION SYSTEM

SUPERPAVE system

Fatigue – Control parameter

Question

Why do we need to consider a maximum value of $G^* \cdot \sin\delta$?

Answer

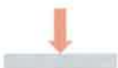
We need to reduce the dissipation of energy at each loading cycle in order to guarantee a sufficient resistance to fatigue damage

The parameter needs to be controlled in representative conditions (long-term aged)

PERFORMANCE-BASED CLASSIFICATION SYSTEM

SUPERPAVE system

Thermal cracking – Control parameter



BBR test

$t_{loading}$ = 60 s

$T_{minimum\ design}$ + 10°C

(the increase of 10°C allows the reduction of loading time from 2 h to 60 s, based on the equivalence principle)

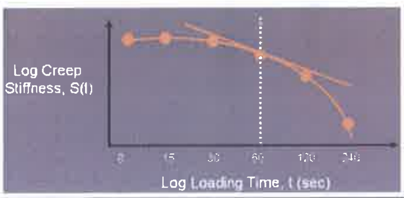
Critical conditions:
- Cold climate
- Quick reduction of temperature

S_{60} on PAV-aged bitumen ≤ 300 MPa

m_{60} on PAV-aged bitumen ≥ 0,3

$$m = \left|\frac{d\log S}{d\log t}\right|$$

creep rate



IMPROVEMENTS TO SUPERPAVE

Limits of the SUPERPAVE system

In the case of modified binders the SHRP-SUPERPAVE approach is not always efficient (underestimate of effective properties and performance implications).

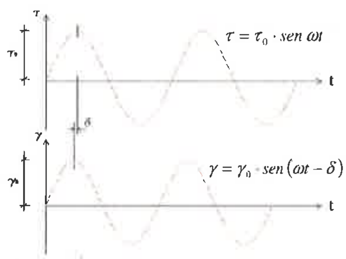
Improvements have been proposed to overcome such a limit in terms of :

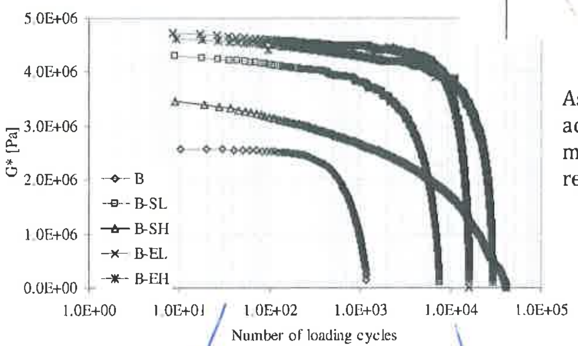
- FATIGUE CHARACTERIZATON (*Time Sweep Tests*)
- PERMANENT DEFORMATION CHARACTERIZATION (*Multiple-Stress Creep Recovery Tests*)

IMPROVEMENTS TO SUPERPAVE

Time Sweep Tests (NCHRP 9-10)

DSR test carried out at constant temperature and frequency until failure





As a result of damage accumulation, the complex modulus is progressively reduced

constant behaviour for the first cycles

increasing number of cycling G* decreases until the complete distruction of the material

IMPROVEMENTS TO SUPERPAVE

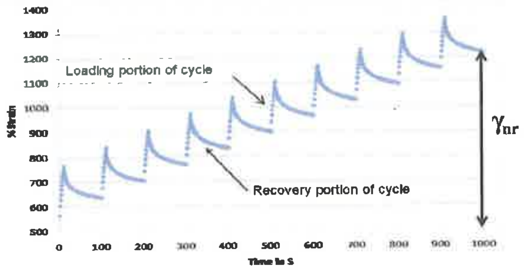
MSCR (massacre test)

***Multiple-Stress Creep Recovery* Tests (AASHTO TP 70-10)**

DSR test carried out at constant temperature and frequency imposing repeated creep-recovery cycles at different stress levels

10 cycles of creep (1 s) and recovery (9 s) :

- 0,1 kPa
- 3,2 kPa



Performance index

(*Non-recoverable creep compliance*)

$$J_{nr} = \frac{(\gamma_{nr}/10)}{\tau}$$

$\Downarrow$

$J_{nr0.1}$

$J_{nr3.2}$

1. Using the elementary bending theory, calculate the time-dependent flexural creep stiffness ($S(t)$), in MPa, expressed with three significant figures.
2. Plot on a bi-logarithm scale, stiffness versus time and fit experimental data with a second-order polynomial function and report regression coefficients (A, B and C) and correlation coefficient (R^2).
3. Estimate m-value (m) by the first derivative of the polynomial function.
4. Verify if this bitumen can be graded as PGXX-28.

Example #3 Dynamic test (DSR)

The two curves shown in Figure 1 represents torque (M) (applied) and deflection angle (φ) (measured the response) monitored during a time sweep test performed with a DSR equipped with a PP08 measuring system and 2 mm gap.
Estimate:

1. Angular frequency (ω) in rad/s, expressed with two significant figures.
2. Norm of the complex shear modulus ($|G^*|$), in MPa.
3. Phase angle of the complex shear modulus (δ) in deg.

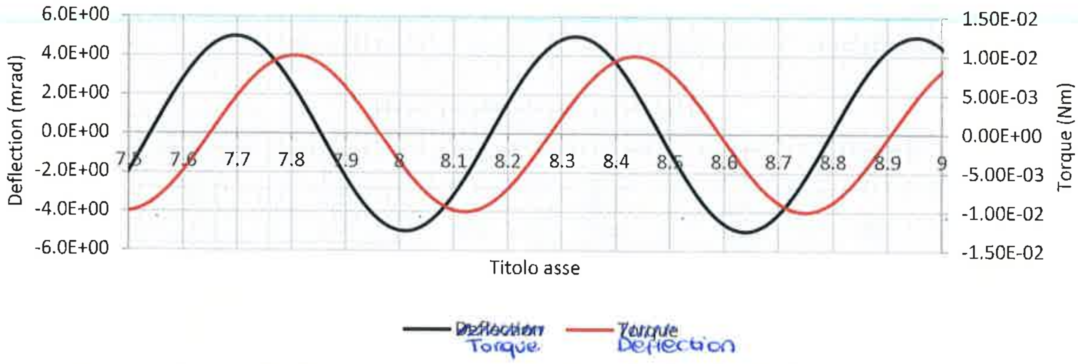


Figure 1 Deflection and torque versus time in dynamic loading of a viscoelastic material

Example #4 Master curve (DSR) → in theory from very low to very high frequency → in practical range is lower

Frequency sweep tests ranging from 1 to 100 rad/s were performed on a bitumen at four different temperatures. The 25 mm parallel plates were used at 60 °C and 80 °C (and 40°C), while the 8 mm parallel plates were employed for tests at 0 °C and 20 °C. Complex shear modulus ($|G^*|$) and phase angle (δ) obtained from DSR tests at selected temperatures and frequencies are shown in Table 3.

1. Construct the master curve for the dynamic shear modulus for a reference temperature (T_R) of 20 °C by manual shifting.
2. Made a semi-log plot of the obtained shift factors (a_T)versus temperature and apply William-Landel-Ferry (WLF) equation. The parameters of the curve C_1 and C_2 can be obtained by minimizing the sum of the squares differences between experimental shift factors and shift factors estimated with the WLF equation.
3. Plot with log-log scale the master curve for $|G^*|$ and δ. (not in a log scale G^*) ~ lin-log
4. Fit the master curve with the Christensen-Anderson model (CA). Fitting parameters G_g, ω_0 and R can be obtained by minimizing the sum of the squares difference between measured and estimated complex shear modulus.

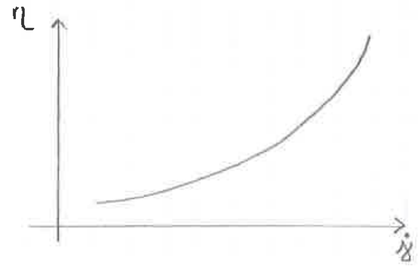
PACIANO

ALEXANDRE

AC.

Performance Grade	PG 46			PG 52							PG 58					PG 64					
	34	40	46	10	16	22	28	34	40	46	16	22	28	34	40	10	16	22	28	34	40
Average 7-day max pavement design temp, °C[b]	<46			<52							<58					<64					
Min pavement design temperature, °C[b]	>−34	>−40	>−46	>−10	>−16	>−22	>−28	>−34	>−40	>−46	>−16	>−22	>−28	>−34	>−40	>−10	>−16	>−22	>−28	>−34	>−40
Original Binder																					
Flash point temp, T 48, min °C	230																				
Viscosity, T 316:[c] max 3 Pa·s, test temp, °C	135																				
Dynamic shear, T 315:[c] G*/sinδ,[d] min 1.00 kPa test temp @ 10 rad/s, °C	46			52							58					64					
Rolling Thin-Film Oven Residue (T 240)																					
Mass change,[e] max, percent	1.00																				
checc at which T G*/senδ = 2,2 ← Dynamic shear, T 315: G*/sinδ,[d] min 2.20 kPa test temp @ 10 rad/s, °C	46			52							58					64					
Pressurized Aging Vessel Residue (R 28) → long term																					
PAV aging temperature, °C[f]	90			90							100					100					
Dynamic shear, T 315: G* sinδ,[d] max 5000 kPa test temp @ 10 rad/s, °C	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13	31	28	25	22	19	16
Creep stiffness, T 313:[g] S, max 300 MPa m-value, min 0.300 test temp @ 60 s, °C	−24	−30	−36	0	−6	−12	−18	−24	−30	−36	−6	−12	−18	−24	−30	0	−6	−12	−18	−24	−30
Direct tension, T 314:[g] Failure strain, min 1.0% test temp @ 1.0 mm/min, °C	−24	−30	−36	0	−6	−12	−18	−24	−30	−36	−6	−12	−18	−24	−30	0	−6	−12	−18	−24	−30

Performance Grade	PG 70						PG 76					PG 82				
	10	16	22	28	34	40	10	16	22	28	34	10	16	22	28	34
Average 7-day max pavement design temperature, °C[b]	<70						<76					<82				
Min pavement design temperature, °C[b]	>−10	>−16	>−22	>−28	>−34	>−40	>−10	>−16	>−22	>−28	>−34	>−10	>−16	>−22	>−28	>−34
Original Binder																
Flash point temp, T 48, min °C	230															
Viscosity, T 316:[c] max 3 Pa·s, test temp, °C	135															
Dynamic shear, T 315:[c] G*/sin δ,[d] min 1.00 kPa test temp @ 10 rad/s, °C	70						76					82				
Rolling Thin-Film Oven Residue (T 240)																
Mass change,[e] max, percent	1.00															
Dynamic shear, T 315: G*/sin δ,[d] min 2.20 kPa test temp @ 10 rad/s, °C	70						76					82				
Pressurized Aging Vessel Residue (R 28)																
PAV aging temperature, °C[f]	100 (110)						100 (110)					100 (110)				
Dynamic shear, T 315: G* sin δ,[d] max 5000 kPa test temp @ 10 rad/s, °C	34	31	28	25	22	19	37	34	31	28	25	40	37	34	31	28
Creep stiffness, T 313:[g] S, max 300 MPa m-value, min 0.300 test temp @ 60 s, °C	0	−6	−12	−18	−24	−30	0	−6	−12	−18	−24	0	−6	−12	−18	−24
Direct tension, T 314:[g] Failure strain, min 1.0% test temp @ 1.0 mm/min, °C	0	−6	−12	−18	−24	−30	0	−6	−12	−18	−24	0	−6	−12	−18	−24



$\eta = k\dot{\gamma}^n$

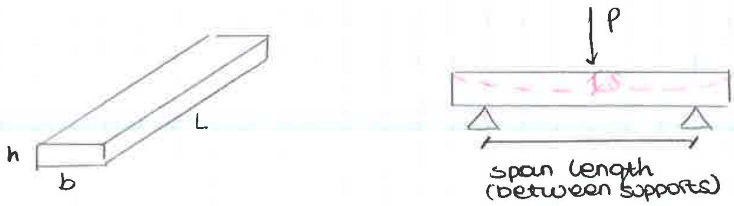
EX 2

→ beam made of bitumen, tested at low temperature ⇒ bitumen becomes solid and we can test the beam placing two supports and a central load

constant (we usually use a bath)

→ 3 point bending test

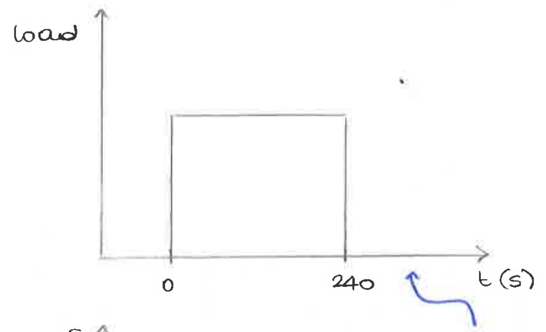
→ We misure vertical displacement δ

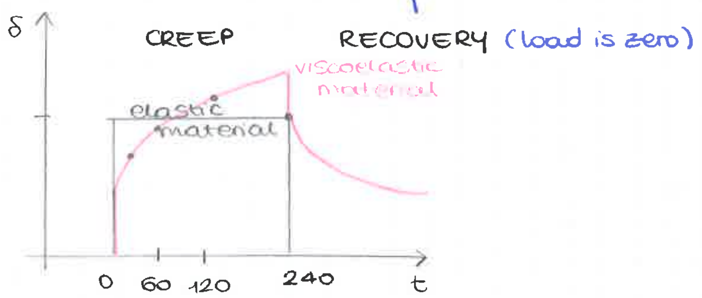


It behaves as viscoelastic material so δ doesn't appear immediately but as a function of time

$\delta(t)$

⇒ we performe a **CREEP TEST**





1) $S(t) = \dfrac{1}{D(t)}$ → deformability

→ stiffness of material (it's like an elastic modulus, but it isn't because it depends on time)

$S(t) = \dfrac{\sigma_0}{\varepsilon(t)}$

→ we can find it exactly through this creep test

$\delta = \dfrac{PL^3}{48EI}$

04/12/2017

POLITECNICO DI TORINO
Master Course
in Civil Engineering
2017-18

Construction of Roads, Railways and Airports (01RVMMX)

ROAD AND AIRPORT PAVEMENTS
Bituminous ~~binders~~ mixtures

*
Volumetrics : how the 3D organisation is. Binder around 5% of the total mass. The density of bitumen is around 1,2, for aggregate it's around 2,2
=> volume of binder is larger than 5%; for residual voids we have 20 or 25%.
for dense-graded mixture we have 4-10% (too small voids are not good because for thermical variation bitumen increases its volume so it will oversize the mixture if it hasn't the space to grow).
=> dimentions of aggregates around 3cm or less (1 cm)

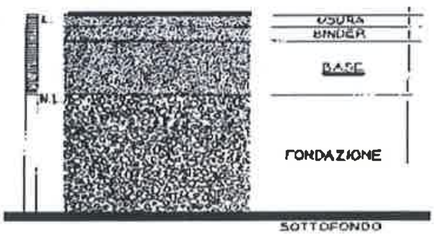
BASICS

BITUMINOUS MIXTURES

very fine portion of aggregates
bitumen covers aggregates but not filler (they are mixed with bitumen)

Composite materials constituted by aggregates, filler and bitumen
mastic

Employed for the construction of the upper bound layers of flexible pavements



Bitumen-bound layers

Layers are different in terms of:

- Thickness — it grows from the top to the base ↓+
- Composition — it changes because of the max dimension of aggregates ↑+
- Volumetrics * — higher binder content towards the top because diameters of aggregates increase.

=> DENSE-GRADED MIXTURE : size distribution is continuous the voids are filled with aggregates with small dimensions
↳ very compact with a small fined void content (% of binder)

=> OPENED-GRADED : residual void content to garantee specific properties (such as to lead infiltration of water
↳ DRAINED away from the top and then away not inside the pavement ~ for the top layers

1

→ we use water to check the bounds between aggregate and bitumen because it will lead to detachment

BITUMEN – AGGREGATE AFFINITY

Durability of a bituminous mixture depends upon the stability of the interactions between bitumen and aggregates

mantein stable in time

Water can cause a loss of adhesion, as a result of the combined action of mechanical and chemical effects

macroscopical effect

STRIPPING

Removal of binder film from the surface of the aggregate.

BITUMEN – AGGREGATE AFFINITY

→ old italian specifications

Stripping test (CNR 138/92)

Carried out on aggregate fractions 6,3-10 mm and 10-15 mm

PROCEDURE

- washed and dried aggregates (500 g);
- mixing with binder ((3 or 3,5%); not a real mixture, it's just a reference system
- cooling to room temperature;
- adding of demineralized water at 25°C for 24h
- same procedure at 40°C

soking with water

↳ or boil water

Visual evaluation of degree of stripping (in percent) after 24 hours of immersion

↳ if there isn't affinity aggregates change colors (we see effects of stripping)

⟹ simple test, quick

VOLUMETRIC CHARACTERISTICS

cilindrical sample

Laboratory testing

- **Density of compacted mixture**

Three measurement:
- mass of dry spercimen (M_D)
- mass of specimen in water(M_W)
- mass of specimen saturated but surface dried (M_{SSD})

$$MV = \frac{M_D}{M_{SSD} - M_W} \cdot \gamma_w$$

- **Theoretica maximum density (ASTM D2041)**

Determined on loose mixtures with the picnometer method

M_A = mass of sample in air

M_P = mass of picnometer filled with water

M_{P+G} = mass of picnometer with sample, filled with water

H = correction factor

T = water temperature

$$MMVT = \frac{M_A}{(M_A + M_P) - (M_{P+G} + H)} \cdot \frac{\gamma_{W,T}}{0{,}997}$$

application of the Archimede's principle

VOLUMETRIC CHARACTERISTICS

Laboratory testing

- **Void content(%)**

$$v = 100 \cdot \left(1 - \frac{MV}{MMVT}\right)$$

< MMVT

measure of degree of compaction → so void content is the complementary of degree of compaction

- **Voids in the mineral aggregates (%)**

$$VMA = v + \frac{\%B_{miscela} \cdot MV}{\rho_{bitume}}$$

composition of mixture → %B respect of dry aggregates (for a plan producer)
%B respect of the total mixture → European standards

- **Voids filled with bitumen (%)**

$$VFA = \frac{VMA - v}{VMA} \cdot 100$$

If 1 and 2 are defined, the 3 is a consequence.

05/12/2017

COMPACTION

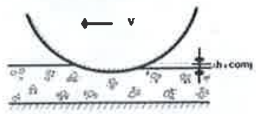
COMPACTION

A proper compaction allows:

- Prevention of post-campaction undr traffic
- Ensures adequate mechanical properties
- Guaratees impermability
- Limits oxidation of binder

Ease of compaction depends upon several factors:

- Mixture properties (aggregates, size distribution, binder)
- temperature
- Layer thickness
- Equipment



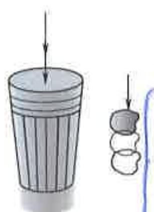
LABORATORY CHARACTERIZATION

COMPACTION

MARSHALL technique

Compaction is carried out in cylindrical moulds by means of a falling mass (from a pre-defined height)

- D = 101,7 mm, h ≅ 63,5 mm
- 50 or 75 blows per face



LIMITS

Aggregates are displaced mainly in the vertical direction by means of a pulse action (**not simulative**)

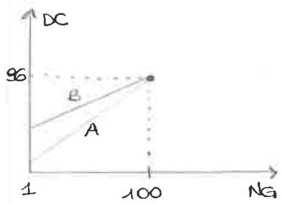
It is not possible to control how compaction evolves (**workability**)

The roller goes and produces a kneading action (impasto) to have a good organisation of pavement (≠ from Marshall)

Bitume	Temperature di equiviscosità	
	mescolamento	costipamento
B 180/200	141 ± 5° C	131 ± 5° C
B 80/100	152 ± 5° C	142 ± 5° C
B 60/80	150 ± 5° C	148 ± 5° C
B 40/50	165 ± 5° C	155 ± 5° C

05/12/2017

Ex. 2 different mixtures



Test of samples representative of field pavements

COMPACTION

Measure of workability (pre-requisite)

During the test the aquisition systemrecords the variation of specimen height as a function of the number of rotations

↳ monitored during the test

Processed data allow the determination of the compaction curve

DEGREE OF COMPACTION

C (%) = 100 (1-v)

↳ complement of 100 of void content

SELF-COMPACTION

$C_1 = C\ (n_G = 1)$

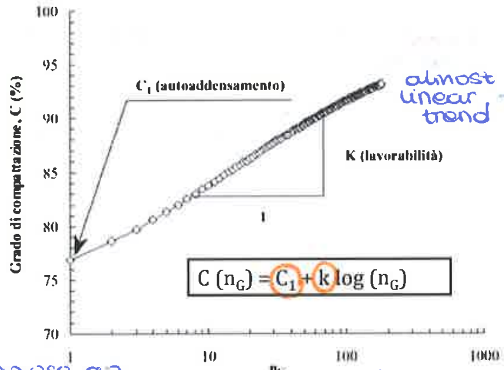
↳ not too high

WORKABILITY

$k = \Delta C / \Delta \log(n)$

energy

Compaction gradient



almost linear trend → in semi logarithmic plane

so in this way we can use an higher value of energy to reassign sample rearrange particles in a better way → if not we need a less value of energy

The curve is built measuring not final weight and degree of compaction, but the machine measures the progressive thickness (height) then we can measure density, void index and grade of compaction

h → MV & TMD → v → C

MECHANICAL PROPERTIES - Stiffness

It is a fundamental property of bituminous mixtures and is related to their stress-strain response under external loading.

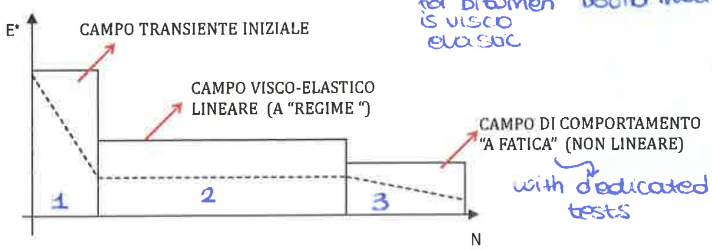
↳ behaviour depends also to contact between particles (elastic behaviour)

STIFFNESS → depends upon:

- Temperature
- Frequency and/or loading time
- Stress state / strain level (non-linearity)

they change stiffness as bound material

for bitumen is visco elastic



with dedicated tests

Mechanical response as a function of increasing cyclic loadings.

1) Find a stable condition
2) For a long time
3) As result of damage

} ≠ phases of loading time of mixture

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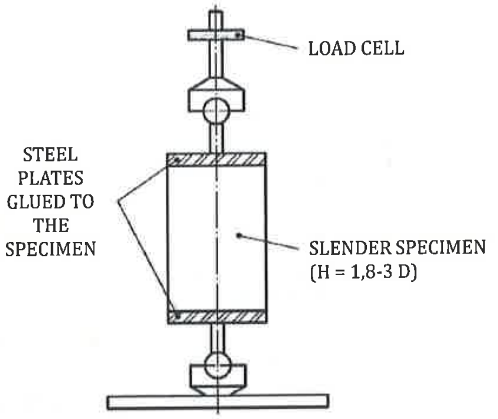
MECHANICAL PROPERTIES - Stiffness

Dynamic tests → uniaxial configuration
(EN 12697-26:2004 – *Direct Tension Compression Test*)



$$\varepsilon = \varepsilon_o \cdot \sin(\omega t)$$

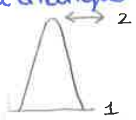
↓

Application of a sinusoidal axial strain ($\varepsilon_0 < 25 \cdot 10^{-6}$)

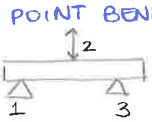
E*, δ changing temperature, frequency (= built Master curves as for binders)

---

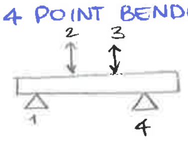
1) 2 POINT BENDING
↳ not a prism, a triangle



2) 3 POINT BENDING



3) 4 POINT BENDING



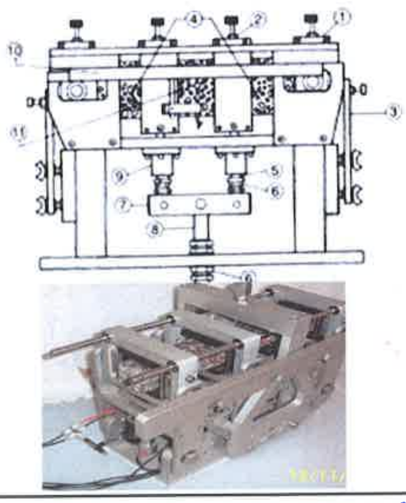
2M)

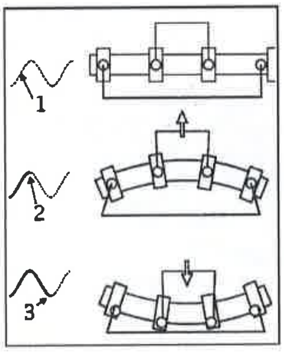
there is only one section subjected to max moment

MECHANICAL PROPERTIES - Stiffness

4 points where we apply loads

Dynamic tests → <u>four point bending</u> configuration → we don't work with a slender cilindre
(EN 12697-26:2004 – *Four Point Bending Test*)





Sinusoidal oscillation of central clamps
↓
4 clamps
↳ 2 external clamps don't move + 2 internal ones oscillate

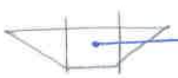
COMPLEX MODULUS

$$E^* = \frac{23 \cdot PL^3}{108 bh^3 \delta}$$ } Muller - Bernoulli theory

L: distance between of external clamps
b, h: dimensions of the section
δ: displacement of the centre of the beam

↳ we use a prisms from fields th n use a small roller

3M)



uniform moment → more uniform distribution of stresses

3T)

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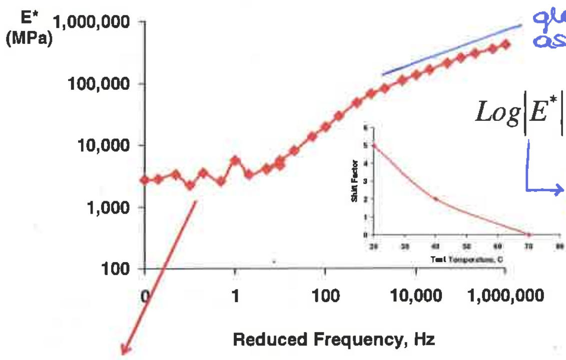
MECHANICAL PROPERTIES - Stiffness

Complex modulus → master curves



glassy asymptote → upper limit

$$Log\left|E^*\right| = \delta + \frac{\alpha}{1+e^{\beta+\gamma(\log t_r)}}$$

↳ classical equation for complex modulus of bituminous mixture

No viscous asymptote → contribution of aggregate skeleton (it's tested the behaviour of skeleton, of unbound material)
↳ lower limit

MECHANICAL PROPERTIES – Fatigue resistance {for repeated loading

Fatigue tests are usually carried out by employing the same equipment and configuration used for stiffness testing

Reference standard

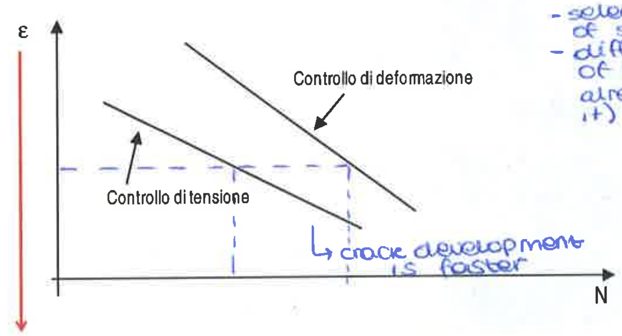
EN 12697-24:2005

⇒ For a number of cycles higher until we damage material
than before

7

MECHANICAL PROPERTIES – Fatigue resistance

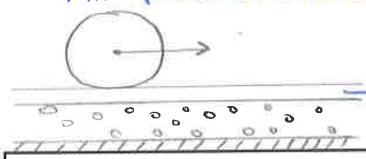
Experimentally it is observed that strain-controlled tests lead to a higher number of cycles to failure than stress-controlled tests . we need to say what to choose.



- select a level of strain
- differentvalues of Nf (we've already known it)

NB. Same controlling parameter (initial strain)

⟹ thick pavements behave in stress control
thin pavements behave close to strain control
not a rigid distinction they tent to

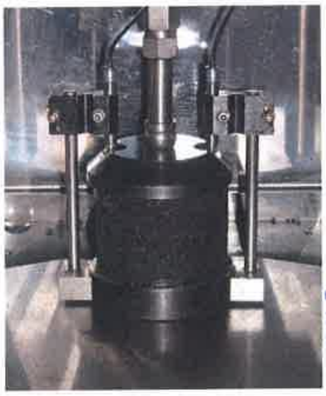


→ it has an imposed displacement (thin)
if it is thick it behaves as a slabs (so stress control)

MECHANICAL PROPERTIES – Permanent deformations

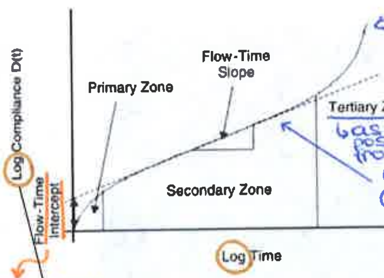
Resistance of accumulating
macroscopic evidence it's creation of ruts

Creep test



Uniaxial loading configuration with no lateral confinement

- vertical loads
- loads constant in time (homogeneous stress distribution)



very fast increase of stress

non linear response in time

as far as possible from the origin

linear development (true flow/viscous behaviour)

neglecting the first part of visco-elastic behaviour we can characterize the material by this intercept

Creep evolution in time

$J(t) = \varepsilon(t) / \sigma_0$ → **Compliance** (inverse of stiffness)

$\varepsilon = \dfrac{\text{displacement}}{\text{initial height}}$

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MECHANICAL PROPERTIES – Permanent deformations

Uniaxial compression test (EN 12697-25:2005 - *Uniaxal Cyclic Compression Test*)

Test conditions

- Applied stress = 100 kPa
- Number of loading cycles = 3600 (2 h)

Parameters

$$\varepsilon_n = 100 \cdot \left(\frac{h_0 - h_n}{h_0} \right) \longrightarrow$$ **Permanent strain after n cycles**

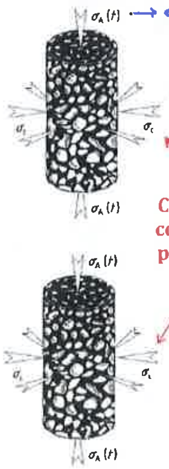
$$f_C = \frac{\varepsilon_{n1} - \varepsilon_{n2}}{n_1 - n_2} \longrightarrow$$ ***(Creep Rate)*** {slope of a curve}

$$E_n = \frac{\sigma}{\varepsilon_n} \cdot 1000 \longrightarrow$$ **Creep modulus after n cycles**

factor to convert different used unites

MECHANICAL PROPERTIES – Permanent deformations

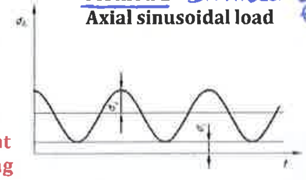
Triaxial cyclic compression test (better)
(EN 12697-25:2005 - *Triaxial Cyclic Compression Test*)



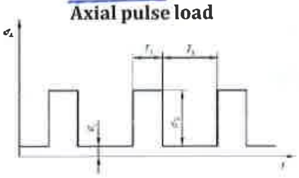
→ deviatoric load

Constant confining pressure

Method 1 similar to 2 (we can choose freely)
Axial sinusoidal load



Method 2
Axial pulse load



Analysis of the linear part of the creep curve

$$\varepsilon_n = A_1 + B_1 \cdot n$$

$$f_C = B_1 \cdot 10^4$$ because of the units which are used

↓

Creep Rate

⇒ similar to resilient modulus of soil

⇒ expensive and operators have to have more skills
better the first test

11

MECHANICAL PROPERTIES – Indirect tensile strength

Allows the determination of a failure parameter

Used for:
- QC/QA and mix design
- Evaluation of resistance at low temperatures (*thermal cracking*)
- Water durability (*Root-Tunnicliffmethod*)

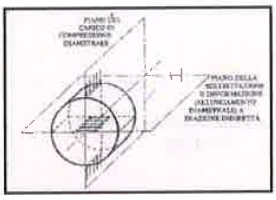
↳ with saturated sample, to compare ITS of this water procedure and the initial value (*) →

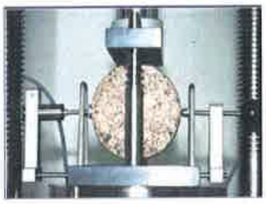
INDIRECT TENSILE STRENGTH (ITS)

resistenza a trazione indiretta ←

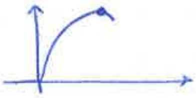
$$RTI = \sigma_t = \frac{2 \cdot P}{\pi \cdot d \cdot t}$$

Load applied quasi-statically with a predefined speed of displacement

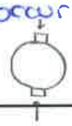




- impose displacement
- read load until the pea



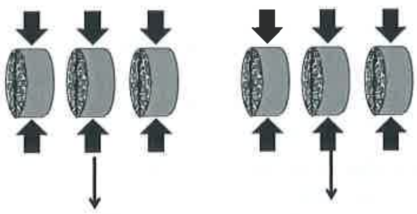
~ distributed on a little area so there, local damages can occur



MECHANICAL PROPERTIES – Indirect tensile strength

(*) **Root-Tunnicliff method (AASHTO T 283)**

6 specimens with %v = 6-8%



no conditioning
(RTI_1)

Saturation and immersion in water at 60°C for 24 h
(RTI_2)

RESIDUAL STRENGTH

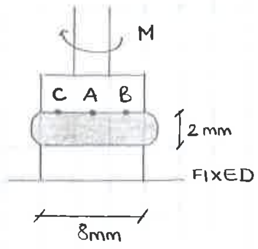
$$ITSR = \frac{RTI_2}{RTI_1}$$

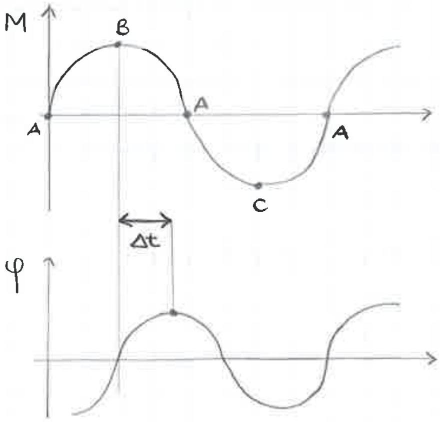
↓

tresholds in specifications (80% it's a typical value)
80 - 85 %

EX 3

12/12/17





In the response there is a lag, a delay (Δt)
↳ Typical of viscoelastic material

$0 < \delta < 90°$

$\delta = 0$ elastic

$\delta = 90$ viscous

$\Delta t = 0 \div \overline{\Delta t}$

$\tau = \dfrac{2M}{\pi R^3}$

$\gamma = \dfrac{R\varphi}{h}$

Through these equations M becomest and φ becomes γ

$|G^*| = \dfrac{\tau_0}{\gamma_0}$ max values of τ and γ

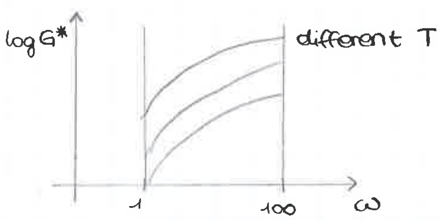
$\boxed{\delta = \omega \cdot \Delta t}$

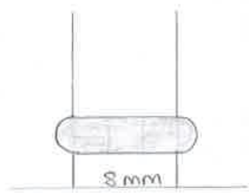
$T = \dfrac{1}{f}$ $\qquad f\,[Hz] = [s^{-1}]$

$\omega = 2\pi f$ $\qquad \omega = [rad/s]$

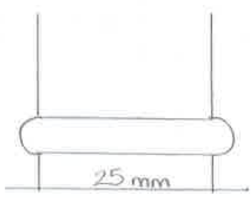
G' and G'' can be computed.

EX 4





Reduce temperature so bitumen becomes stiffer and viceversa.



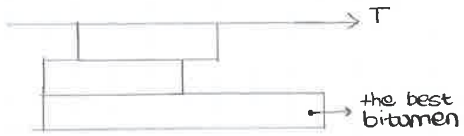
TTS: time temperature superposition principle
↳ we have to verify if it can be used if the points can be linked with only one curve (in the graphic $G^* - \varphi$)

EX 5

1

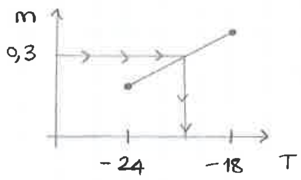
PG: performance grade

- compute
  $\frac{G^*}{\sin\delta}$
  ↳ check at which T the rate is more than 1 (58°C)
  ↳ then at which T is more than 2,2 (52°C
- compute
  $G^* \cdot \sin\delta$
  ↳ check at which T the product is less than 5000
- Check at which T $S<300$ and $m>0{,}300$
  ↳ reduce T of 10°C
  ↳ −28°C

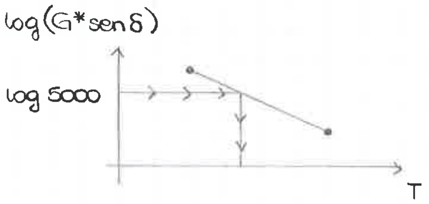


PG garantee same performances in the range of T defined by PG, itself.

2



$$T_c = T_1 + \left(\frac{0{,}300 - m_2}{m_1 - m_2}\right)(T_1 - T_2)$$ → reduced by 10 °C to find the lower PG temperature



$$T_c = T_1 + \left(\frac{\log 5000 - \log G^*\sin\delta_2}{\log G^*\sin\delta_1 - \log G^*\sin\delta_2}\right)(T_1 - T_2)$$

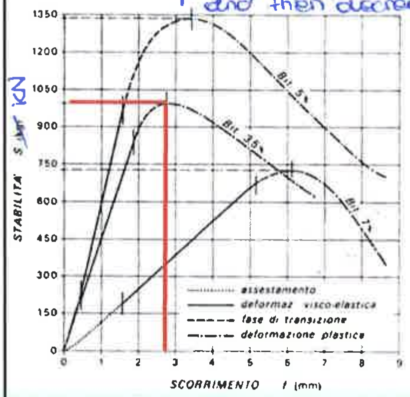
1 PG 58-22 (example)

2 PG 56.6- 22.8 (example)

MIX DESIGN – Marshall method

Stability and flow

↳ grows up to a pick (= failure) and then decreases



Stability (S): maximum load at failure

Flow (s): vertical displacement at failure

↳ high flow corresponds to brittle material and viceversa

Marshall stiffness = S/s

Limits of the test:

Static application of loads

T = 60°C, different from typical service conditions

Mechanical properties: non fundamental (completely empirical)

The "recipe" of the mixture is determined in two phases:

- size distribution of aggregates (skeleton)
- optimal binder content (we use the Marshall test)

MIX DESIGN – Marshall method

Design size distribution

The mixture of aggregates has to satisfy predefined size distribution limits

Standard mixtures (*CIRS*)

Tabella 4.6

Serie crivelli e setacci UNI		Base	Binder	Usura A	Usura B	Usura C
Crivello	40	100	-	-	-	-
Crivello	30	80 – 100	-	-	-	-
Crivello	25	70 – 95	100	100	-	-
Crivello	15	45 – 70	65 – 85	90 – 100	100	-
Crivello	10	35 – 60	55 – 75	70 – 90	70 – 90	100
Crivello	5	25 – 50	35 – 55	40 – 55	40 – 60	45 – 65
Setaccio	2	20 – 35	25 – 38	25 – 38	25 – 38	28 – 45
Setaccio	0.4	6 – 20	10 – 20	11 – 20	11 – 20	13 – 25
Setaccio	0.18	4 – 14	5 – 15	8 – 15	8 – 15	8 – 15
Setaccio	0.075	4 – 8	4 – 8	6 – 10	6 – 10	6 – 10
% di bitume		4.0 – 5.0	4.5 – 5.5	4.8 – 5.8	5.0 – 6.0	5.2 – 6.2

Per i tappeti di usura il fuso A è da impiegare per spessori superiori a 4 cm, il fuso B per spessori di 3 – 4 cm, il fuso C per spessori inferiori a 3 cm.

↳ granulometric bars BANS

for each sieve we have the range accepted in which we have the percentage of passing

Open-graded mixtures (*CIRS*)

Tabella 6.5.1

Serie crivelli e setacci UNI		%Passanti
Crivello	20	100
Crivello	15	80 – 100
Crivello	10	20 – 40
Crivello	5	15 – 25
Setaccio	2	10 – 20
Setaccio	0.4	8 – 12
Setaccio	0.18	7 – 10
Setaccio	0.075	5 – 7

Non-continuous curve

(in such case, specimens are compacted with 50 blows per face)

plotting these values we obtain almost continue curve