Long term behavior of two component back-fill grout mix used in full face mechanized tunneling

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In mechanized tunneling the annular gap between the segmental lining and the surrounding soil caused by tunnel driving, must be backfilled almost instantaneously with an adequate grouting mortar when tunnelling in soils and particularly in urban area at low overburden. The main goal of this research is to investigate the grouting performance of two-component grout mix also when long curing time is considered.
Keywords: *mechanized tunneling, shield, back-filling, two-component grout, laboratory test.*

Comportamento a lungo termine di miscele bicomponenti usate nello scavo meccanizzato. *Nello scavo meccanizzato il vuoto anulare che si viene a creare a tergo dei conci dovuto al sovrascavo deve essere riempito praticamente in modo istantaneo con l'uso di indonee miscele cementizie. Questa operazione è particolarmente importante negli scavi nei terreni, in area urbana a bassa copertura. Lo scopo principale di questa ricerca è quello di analizzare il comportamento e le prestazioni delle miscele bicomponente anche dopo lunghi tempi di maturazione.*
Parole chiave: *Scavo meccanizzato, scudi, backfilling, miscela bicomponente; prove di laboratorio.*

Performance de coulis bi-composants utilisés dans l'excavation mécanisée. *Dans l'excavation mechanizée, l'ouverture entre l'anneau de voussoirs et le terrain environnant, causée par l'excavation du tunnel, doit être remplie immédiatement avec injection de mortier. Cette opération est particulièrement importante pour l'excavation du tunnel en sols, surtout avec petites couvertures. L'objectif principal de cette recherche est l'étude des performances de coulis bi-composants aussi après longues périodes de maturation.*
Mots clés: *excavation mécanisée, boucliers, injection de remplissage, coulis bi-composant, tests de laboratoire*

1. Introduction

The filling of the void annulus which is created behind the shield tail between the segment lining and the grout is an operation of paramount importance to minimize surface settlements ensuring a uniform, homogeneous and immediate contact between ground and lining; lock the segment lining into position, avoid movement owing to both segmental self-weight and the thrust forces, hoop stresses, generated by the TBM; bear the loads transmitted by the TBM back-up weight; avoid or limit the occurrence of punctual loads of the lining and improve waterproofing action of the gaskets (Thewes and Budach, 2009; Pelizza *et al.*, 2010; Peila *et al.*, 2011).

For correctly achieving all the above mentioned goals, the injected material should harden ideally instantaneously and the void annulus should be regularly and completely filled. From the operational point of view, the injection system should guarantee the reliability of the system in terms of transportability of the mix. Moreover the grout should not choke the injection pipes and the injected material should be homogeneous and durable in respect to its physical characteristics and mechanical behavior.

2. Two component mix

The two-component mix is typically a super fluid grout, stabilized in order to guarantee its workability for a long time, to which an accelerator admixture is added at the injection point at the shield tail (Peila *et al.*, 2011; ITAtech Report, 2014). Few seconds after the addition of the accelerator (normally 10-25 seconds, during which the TBM advances approximately 2-15 mm). The mix gels it exhibits a thixotropic consistency and start developing mechanical strength almost instantaneously. Furthermore, the use of a retarding agent is able to inhibit the mix from setting thereby guaranteeing its workability for very long time after batching (up to 72 hours when necessary): this facilitates stockpiling grout in the mixer-containers that are usually bigger than the theoretical volume of material to be injected for every ring.

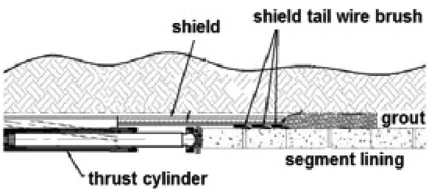

Fig. 1. Scheme of the shield tail backfilling.
Schema dell'iniezione di coda.

3. Examples of applications of the two components mix

Some significant examples of tunnelling projects, in different countries, where the two-component system was used for the back-filling operation, are shortly described in the following to show the field of application of this type of technology.

3.1. Metro Rome Line C – Rome (Italy)

The line C of the metro of Rome was excavated with four Herrenknecht EPB machines (6.7 m diameter) from 2008 to 2011. The excavated soil is partly a low-permeable and stable pozzolana, partly clay and a permeable sandy soil. The excavation was above and below the water table. The used two-component system has the mix design reported in tab. 1 (Pelizza *et al.*, 2011) (fig. 2).

3.2. Oraki Main Sewer Hobson Diversion – Auckland (New Zealand)

The project concerns the excavation of a 4.3 m diameter mixed-face shield. The project requirements were particularly high in terms of mechanical strength to be achieved, even at long term. In particular, the two-component material had to achievea UCS value of 0.1 MPa after 30 minutes and 5 MPa after 28 days. The only way to achieve so great values was to use higher amount of cement than typically (480 kg per cubic meter of hardened material). At the same time, the grout was not pumpable enough with such an amount of cement and the addition of a super-plasticizer admixture was necessary (Tomoya *et al.*, 2009). Such a mix guaranteed proper pumpability and stability properties to the fresh grout and was able to achieve average values of compressive strength after 28 days from batching of 5.1 MPa.

3.3. Metro Line 1 in Brescia (Italy)

The project concerns the construction of a metro line tunnel in alluvial ground with a tunnel diameter of 9.15 m excavated by an EPB machine below and above the water table. The composition of the used two component mix is summarized in tab. 3.

3.4. Metro Line 2 in Prague (Czech Republic)

Metro Line 2 line in Prague was excavated with two Herrenknecht EPB machines from 2010 to 2012. The excavated soil is silt and sand above and below the water table. The backfilling was carried out with a two-component grout (fig. 3).

Fig. 2. Hardened two component mix below the segments and the soil as shown in the excavation of the station Centocelle. (photo Mapei's archive).
Miscela indurita tra i conci ed il terreno come appare nello scavo della stazione di Centocelle (fotografia archivio Mapei).

Tab. 1. Two component mix used in Metro C Line in Rome (values per m^3) (Pelizza *et al.*, 2011).
Mix design della miscela bi-componente usata nello scavod elle gallerie della Metro C a Rome (i valori sono indicati al m^3) (Pelizza et al., 2011).

Water	770-820 kg
Bentonite	30-60 kg
Cement	320-350 kg
Retarding agent by Mapei	3-7 l
Accelerator admixture by Mapei	50-100 l

Tab. 2. Two component mix adopted in Oraki Main Sewer Hobson Diversion – Auckland (values per m^3) (Tomoya **et al.**, 2009).
Mix design della miscela bi-componente usata nello scavo delle gallerie della Oraki Main Sewer Hobson Diversion ad Auckland (i valori sono indicati al m^3) (Tomoya et al., 2009).

Water	730 kg
Bentonite	30 kg
Cement	480 kg
Retarding agent by Mapei	1 l
Super-plasticizer by Mapei	5 l
Accelerator admixture by Mapei	50 l

Tab. 3. Two component mix adopted in the metro line of Brescia (values per m^3) (Mapei data).
Mix design della miscela bi-componente usata nello scavo delle gallerie metropolitan di Brescia (i valori sono indicati al m^3) (dati forniti da Mapei).

Water	816 kg
Bentonite	42 kg
Cement	315 kg
Retarding agent	3 l
Accelerator admixture	60 l

3.5. Metro Line 2 in Warsaw (Poland)

The Metro Line 2 line in Warsaw was excavated with four Herrenknecht EPB machines from 2012 to 2013. The geology is extremely heterogeneous with two main types of

Fig. 3. View of the hardened grout as can be seen in the enlargement for a station in Prague Metro (photos Mapei's archive).
Vista della miscela indurita a tergo dei conci come visibile nell'allargo di una stazione nella metropolitana di Praga (fotografia archivio Mapei).

soil: over-consolidated impermeable clay and mono-granular sand below the water table. The backfilling was carried out with a two-component grout with the composition summarized in tab. 4 (fig. 4).

Tab. 4. Two component mix adopted in the metro line of Warsaw (values per m^3) (Mapei data).
Mix design della miscela bi-componente usata nello scavo delle gallerie metropolitana di Varsavia (i valori sono indicati al m^3) (dati forniti da Mapei).

Water	809 kg
Bentonite	40 kg
Cement IV B 32.5 N	300 kg
Retarding agent by Mapei	5 l
Accelerator admixture by Mapei	65 l

3.6. Legacy Way traffic tunnel in Brisbane (Australia)

The Legacy Way tunnel in Brisbane was excavated by two Herrenknecht double shield machines from 2012 to 2014 inside a compact rock mass (sandstone, meta-basalt and conglomerates). In fig. 5 a test site developed before the excavation to check how the mix flows in the annulus and how it hardens is illustrated. This is one of the first examples of rock shield TBM that used the two component mix.

Fig. 4. View of the hardened grout as can be seen in the enlargement for a station. It is possible to observe how the mix fills completely the void annulus (photo Mapei's archive).
Vista della miscela indurita a tergo dei conci è ben visibile come la miscela riempia molto bene anche delle irregolarità dello scavo (fotografia archivio Mapei).

Fig. 5. Test site developed before the starting of the excavation in Brisbane (photos Mapei's archive).
Campo prove sperimentale prima dello scavo a Brisbane (fotografia archivio Mapei).

3.7 Hydraulic tunnel Maldonado in Buenos Aires (Argentina)

The hydraulic tunnel Maldonado in Buenos Aires was excavated with two EPB Lovat from 2009 to 2012. The geology is mainly sand with variable percentage of silt. In fig. 6 the result of backfilling in a shaft from the surface reaching the tunnel is clearly shown. The backfilling was carried out with a two-component grout with the composition of tab. 5.

Tab. 5. Two component mix adopted in the tunnel Maldonado in Buenos Aires (values per m^3) (Mapei data).
Mix design della miscela bi-componente usata nello scavo della galleria di Maldonado a Buenos Aires (i valori sono indicati al m^3) (dati forniti da Mapei).

Water	796 kg
Bentonite	35 kg
Cement TYPE IV	350 kg
Retarding agent by Mapei	5 l
Accelerator admixture by Mapei	61 l

3.8. LTA tunnels – Singapore

Another important reference, regarding the use of the two-component mix, is the construction of the LTA tunnels in Singapore, which included approx. 20 lots for a total of more than 50 km of tunnels. The use of a two component mix was successful with different types of TBMs (EPB, Slurry Shields), manufactured by different suppliers, and in variable geological conditions (i.e. clay, alluvium ground, fluvial deposits, granite, gravel, etc.). An example of the composition of the two component mix used in this case is reported in tab. 6.

Tab. 6. Example of the composition of the two component mix adopted in Singapore metro tunnels (values per m^3) (Mapei Singapore data).
Esempio del mix design della miscela bi-componente usata nello scavo delle gallerie della metropolitana di Singapore (i valori sono indicati al m^3) (dati forniti da Mapei Singapore).

Water	810 kg
Bentonite	30 kg
ordinary portland Cement	230 kg
Retarding agent	4 l
Accelerator admixture	80 l

3.9. Highway tunnel Sparvo between Bologna and Firenze (Italy)

The highway tunnel Sparvo on the new highway connection between Bologna and Firenze has been excavated by one EPB machine Herrenknecht with a diameter of 15.4 m (at the execution time the largest TBM-EPB of the world). The work was carried out from 2011 to 2013. The geology is: clay, claystone, with ophiolite intrusions and sandstone. The excavation was carried out above the water table. The specifications of the two component grout mix were (Dal Negro *et al.*, 2014): fluidity (Marsh cone value 30-45"); long workability (up to 72 h); stability (bleeding test <3% after 3 hours); mechanical strength (UCS > 0.1MPa after1 h; UCS > 0.5 MPa after 1 day; UCS > 2 MPa after 28 days); time of gel creation ranging from 5-20". The composition of the two component mix used in this case is reported in tab. 7 (Dal Negro *et al.*, 2014).

Tab. 7. Example of the composition of the two component mix adopted in Sparvo tunnel (values per m^3) (Mapei data).
Esempio del mix design della miscela bi-componente usata nello scavo della galleria di Sparvo (i valori sono indicati al m^3) (dati forniti da Mapei).

Water	795-810 kg
Bentonite	300-330 kg
Cement	40-45 kg
Retarding agent by Mapei	4-5 l
Accelerator admixture by Mapei	60-65 l

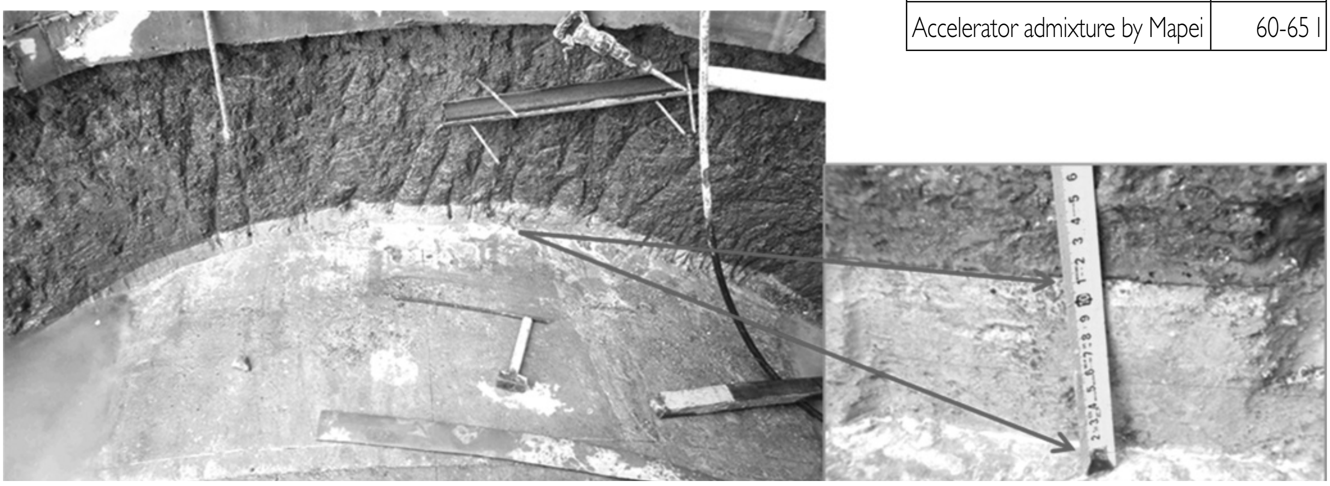

Fig. 6. View of the hardened grout excavated in a portion of the tunnel of Maldonado above the water table. It is possible to observe how the mix fills completely the void annulus (photos Mapei's archive).
Dettaglio della miscela indurita in una porzione della galleria di Maldonato sopra falda. È possibile osservare come la miscela bicomponente riempia completamente il vuoto anulare all'estradosso dei conci (fotografia archivio Mapei).

3.10. *Hydraulic tunnel S.T.E.P., Sections II and III in Abu Dhabi*

The hydraulic tunnel S.T.E.P., Sections II and III in Abu Dhabi, was excavated with 5 EPB Herrenknecht from 2010 to 2013 (Dal Negro *et al.*, 2013). The superficial deposits are made of saturated silty sands followed by a sequence of dry mudstone and gypsum where the tunnel were mainly excavated. Also in this case a two component mix was used with the mix design of tab. 8

Tab. 8. Example of the composition of the two component mix adopted in Abu Dhabi STEP tunnel (values per m³) (Mapei data).
Esempio del mix design della miscela bi-componente usata nello scavo della galleria STEP di Abu Dhabi (i valori sono indicati al m³) (dati forniti da Mapei).

Water	815-825 kg
Bentonite	40 kg
Cement	280-300 kg
Retarding agent by Mapei	3-4 l
Accelerator admixture by Mapei	60-65 l

3.11. *Conclusions obtained from case histories*

All the mentioned examples show that the current trend in mechanized tunnelling is to widely use two-component grout compared with other types of backfilling mixes. From the analysis of the location where the tunnels were excavated after the machine has passed, usually for the construction of the stations, it is possible to assess that the two-component mix is able to completely fill the void annulus (also below the invert) furthermore can be observed that the mix is able to penetrate in the surrounding soil if it is permeable or when it presents over-excavations. Finally the geological field of applications ranges from soils (sand and clay) to rock masses, both above and below the water table.

4. *Results of laboratory test on fresh two component mix*

The results of a series of tests regarding the physical and mechanical behavior of the fresh (not hardened) two-component mix, with the composition of tab. 9, to check its suitability for the EPB tunneling procedure, were reported by Peila *et al.* (2011).

Tab 9. Two component mix tested by Peila *et al.* (2011).
Mix design della miscela bicomponente sottoposta a prova da Peila et al. (2011).

Component	Average quantities [kg/m³]
Water	796
Bentonite	35
Cement type IV/B-P 32.5 R	350
MAPEQUICK CBS SYSTEM 1	6,4
MAPEQUICK CBS SYSTEM 2	84,8

The following tests were carried out by Peila at al. (2011):

- bleeding test (ASTM C940): the test is carried out by leaving undisturbed 500 ml of mix without accelerator for three hours and after measuring the percentage of water separation. A good mix should not exceed the 3%; of water separation
- Marsh cone test (ASTM C185): the test permits to evaluate the fluidity and viscosity of the mix without accelerator. It is carried out using a standardized cone and measuring the time request by 1000 ml of mix to flow that should range between 30 s and 45 s;
- hardening time evaluation: the test is carried out by mixing 500 ml of grout and 48g of accelerator and setting up the time when the mix is no more workable (defined as hardening time).

Globally the results of these tests (tab. 10) highlighted that the studied mix could be easily and safely pumped through the tail skin and that the not accelerated mix was stable (no separation of the solid phase, mainly cement grains) for a long time.

Tab. 10. Results of the tests of the fresh mix (Peila *et al.*, 2011).
Risultati delle prove sulla miscela fresca (Peila et al.,2011).

Sample	Time since the grout was prepared [h]	Bleeding value [%]	Marsh cone time [s]	Hardening time [s]
A	0	3	33	12
B	12	2	32	12
C	24	2	32	13,5

5. *Influence of time and curing conditions of the two-component mix*

To study the effect of curing conditions on the strength of the hardened mix, a set of samples with cubic size of 10cm were prepared in laboratory by mixing the two components and maintained inside sealed buckets filled with sand at different moisture conditions (set 1: from dry to 5% and set 2 from 10% to 15% – percentage of water on the weight of the sand) for a long time, up to 1080 days.

The studied grouts were prepared with two different contents of bentonite (30 kg/m³ and 40 kg/m³) and the mixes are reported in tabb. 11 and 12. The strength values measured in the research are summarized in figs. 7-10.

Tab. 11. Mix design of the two component type A.
Mix design della miscela bicomponente tipo A.

Component mix 1	Average quantities [kg/m³]
Water	826
Bentonite	30
Cement type IV/B-P 32.5 R	290
MAPEQUICK CBS SYSTEM 1	5
MAPEQUICK CBS SYSTEM 2	82

Tab. 12. Mix design of the two component type B.
Mix design della miscela bicomponente tipo B.

Component mix 1	Average quantities [kg/m^3]
Water	823
Bentonite	40
Cement type IV/B-P 32.5 R	290
MAPEQUICK CBS SYSTEM 1	5
MAPEQUICK CBS SYSTEM 2	82

5.1. Conclusions on the effect of curing condition on the behavior of the two component mix

The obtained results highlighted the effect of the curing condition when the samples are maintained in a confined condition at a constant moisture. These data have shown that there is no significant reduction of strength even if the samples are maintained in a dry condition (moisture less than 2%). This result depends probably on the fact that when the system is confined (as in the carried out experiment) the moisture of the grout cannot be released from the grout itself therefore the hardened mix keeps its mechanical properties (while a different behavior is observed when the samples are kept in free air). This result is also confirmed by an experiment carried out by Mapei UTT team who kept in a closed bucket a sample of two component mix produced for Portland job site (USA) for five years: no significant variation of the geometry of the sample was observed (fig. 11).

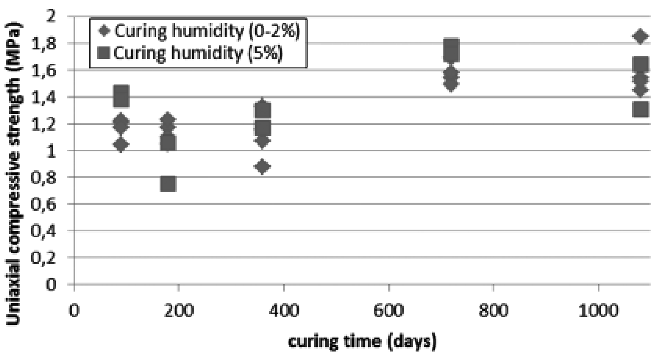

Fig. 7. Results of the uniaxial compressive tests on samples cured in a sealed bucket filled with sand with a controlled humidity content (0-2% and 5%) and maintained at a temperature of about 20-25°C. The used mix is the mix type A (bentonite content of 30 kg/m^3).
Risultati delle prove a compressione monoassiale su campioni maturati in contenitori sigillati riempiti con sabbia ad umidità controllata (0-2% e 5%) e mantenuti alla temperature di circa 20-25°C. La miscela usata è di tipo A (contenuto di bentonite di 30 kg/m^3).

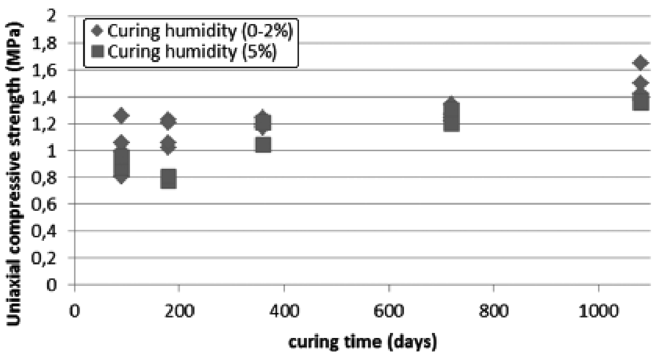

Fig. 8. Results of the uniaxial compressive tests on samples cured in a sealed bucket filled with sand with a controlled humidity content (0-2% and 5%) and maintained at a temperature of about 20-25°C. The used mix is the mix type B (bentonite content of 40 kg/m^3).
Risultati delle prove a compressione monoassiale su campioni maturati in contenitori sigillati riempiti con sabbia ad umidità controllata (0-2% e 5%) e mantenuti alla temperature di circa 20-25°C. La miscela usata è il tipo B (contenuto di bentonite di 40 kg/m^3).

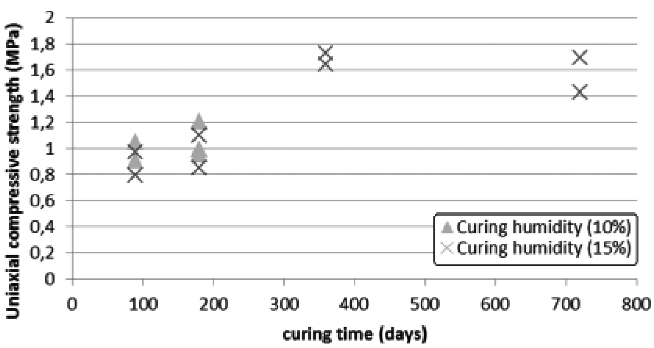

Fig. 9. Results of the uniaxial compressive tests on samples cured in a sealed bucket filled with sand with a controlled humidity content (10% and 15%) and maintained at a temperature of about 20-25°C. The used mix is the mix type A (bentonite content of 30 kg/m^3).
Risultati delle prove a compressione monoassiale su campioni maturati in contenitori sigillati riempiti con sabbia ad umidità controllata (10% e 15%) e mantenuti alla temperature di circa 20-25°C. La miscela usata è il tipo A (contenuto di bentonite di 30 kg/m^3).

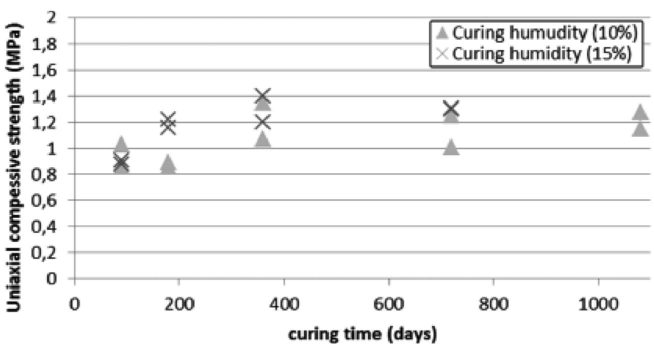

Fig. 10. Results of the uniaxial compressive tests on samples cured in a sealed bucket filled with sand with a controlled humidity content (10% and 15%) and maintained at a temperature of about 20-25°C. The used mix is the mix type B (bentonite content of 40 kg/m^3).
Risultati delle prove a compressione monoassiale su campioni maturati in contenitori sigillati riempiti con sabbia ad umidità controllata (10% e 15%) e mantenuti alla temperature di circa 20-25°C. La miscela usata è il tipo B (contenuto di bentonite di 40 kg/m^3).

Fig. 11. Sample cured at constant humidity after five years of its preparation (Portland Job site, USA – photos Mapei's archive).
Campione di miscela mantenuta in un recipiente sigillato cinque anni dopo la preparazione (cantiere di Portland, USA, fotografie archivio Mapei).

The other important result is that also with the weak mix used for the laboratory tests when the maximum value of strength is reached, this value remains practically stable in time (up to 1080 days).

The variation of the uniaxial strength of the order 0f 0.2-0.3 MPa are completely reasonable taking into account both the samples preparation and the studies low strength mix. It is also clear the effect of the bentonite content on the obtained strength.

Conclusions

The analysis of relevant case histories shows that in a large number of applications with different geological environments ranging from soils (sand and clay) to rock masses, both above and below the water table, the two component backfilling mix was used.

From the real examples it is also possible to observe how the two-component mix is able to fill correctly and completely the void annulus also in invert position and it penetrates in the surrounding soil.

The long lasting curing time tests have shown that if the mix is maintained in a confined space no significant loss of strength can be observed also when a dry environment is considered for a long curing time.

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