# 行政院國家科學委員會專題研究計畫　成果報告

# 垃圾焚化底渣流填料應用於都市管溝回填之研究

計畫類別：個別型計畫
計畫編號：NSC94-2211-E-216-006-
執行期間：94 年 08 月 01 日至 95 年 07 月 31 日
執行單位：中華大學土木與工程資訊學系

計畫主持人：吳淵洵

計畫參與人員：陳怡伶　葉樺姿

報告類型：精簡報告
報告附件：出席國際會議研究心得報告及發表論文
處理方式：本計畫可公開查詢

中　華　民　國 95 年 10 月 27 日

# 行政院國家科學委員會專題研究計畫成果報告

## 垃圾焚化底渣流填料應用於都市管溝回填之研究

## The Application of Incinerator Bottom Ash Flowable Fill for Municipal Pipeline Trench Backfill

計畫編號：NSC 94-2211-E-216-006
執行期限：94 年 8 月 1 日至 95 年 7 月 31 日

主持人：吳淵洵　　中華大學土木與工程資訊系
計畫參與人員：陳怡伶、葉樺姿　中華大學土木與工程資訊系

### 一、中文摘要

由於都市垃圾焚化處理比率逐年提昇，國內垃圾焚化灰渣產量亦逐年增加。過去垃圾焚化廠產出的底渣都是以衛生掩埋處理，但是用地難尋及民眾抗爭因素，衛生掩埋場之闢建極為困難，底渣材料化技術無疑是解決底渣問題的最佳方式。國內工程單位對管溝工程之施工品質控制不良導致施工回填後常發生沉陷與孔洞，對市容及行車安全皆有不良之影響，使用流填料(CLSM)於管溝工程之回填可有效改善此種缺點。以垃圾焚化底渣拌製 CLSM 應用於管溝回填工程確實可行，但因底渣成份複雜且流填料含水量過高，以之應用於都會地區無法符合時效性之需求。

本研究針對底渣流填料於都市管溝回填工程應用所需之早強性予以探討，以配合添加化學摻料之方式執行配比試驗。依據試驗結果，一般型底渣流填料當水固比為 0.35～0.40，灰水比為 0.2～0.3 時，具有較理想之流度值，但齡期 1 天之早期強度均較低，無法符合都市管溝回填之安全要求。添加減水劑、早強劑、速凝劑均可改善底渣流填料之早強性，惟依據試驗結果及統計分析趨勢之判斷，所添加之化學摻料中以早強劑對於早強性之影響最為顯著，於標準流度限制下，建議用量為 1%。超過此限值後，改善早強性則以增加水泥量之方式較為適宜。早強型底渣流填料雖具有長期強度折減之現象，但其 28 天之強度均達設計目標值，故本研究配比設計所得結果應屬可行。

關鍵字：垃圾焚化底渣、都市管溝回填、流填料、CLSM、化學摻料

### Abstract

Because of the limited environment and high density of population, most of the household solid wastes in Taiwan are processed by incineration. However, the large amounts of the incinerator bottom ash (IBA) are difficult to disposal of. Therefore, resource recovery for the IBA has become a very important issue for the environment protection. The varieties of pipeline installations are necessary for the daily life of civilians. However, due to poor construction quality, the backfill of pipeline trench always lead to severe road settlement and pavement deterioration. The limited installation schedule resulting from the congested traffic conditions in a metropolitan area further make things worse.

Flowable fill also known as controlled low strength material (CLSM) is capable of self-hardening, self-compacting, and self-leveling. In comparison with conventional backfill material, CLSM presents advantages such as flowable, free of compaction, adjustable strength, and low settlement. Therefore, it can be used as an ideal alternative for the pipeline backfill. Furthermore, it will present additional environmental values if IBA can be used as aggregate for the flowable fill.

This research conducted an experimental study by mixing IBA with cementitious ingredients to produce flowable IBA (FIBA) and use it for the pipeline backfill in metropolitan area. Experiments include specimen preparation, physical properties, flowability, set time, unconfined compression tests, direct shear tests, CBR values, permeability, and hydrocollapse. Because the mixtures of IBA and cement have shown slow setting behavior, therefore, this research observed the mechanism to cause the slow reaction and developed solutions to reduce the setting time. Based on the results of experiment, use of early strength admixture produced the best early setting of FIBA. The proposed proportion will be 1%. Although use of such mix design may result a reduction of long-term strength, the 28-day strength satisfied the target design value. The findings of this study should provide helpful suggestions for the production of FIBA and its application for the pipeline backfill in metropolitan area. The results tend to reuse IBA, save natural resource of granular fill and ensure the quality of pipeline backfill constructions in most cases.

Key Words: incinerator bottom ash, pipeline backfill, flowable fill, CLSM

## 二、緣由與目的

依據行政院環保署(2005)之統計，台灣每年約產生100萬公噸之垃圾焚化底渣與飛灰，這些灰渣之棄置與處理已造成政府財政上沉重的負擔，並嚴重衝擊環境與生態上之平衡，故探討灰渣再利用並加以推廣極為重要。此外，由於長期以來，台灣各項工程建設之蓬勃發展，造成砂石原料嚴重缺乏，因此研發砂石替代材料已成為延續國家建設之關鍵性因素。

台灣地區目前共有20座垃圾焚化廠，每年產生之垃圾焚化底渣與飛灰，多數均以垃圾掩埋的方式加以處置，其缺點除了土地成本、處理費用昂貴及掩埋場場址難尋外，灰渣所含毒性物質溶出亦可能造成二次污染，故底渣資源化再利用為目前環保工作之重要課題。

填土品質之優劣與管溝工程之成敗及道路交通安危息息相關，影響填土品質之因素中又以夯實效能具決定性之影響。國人工程習性不佳，對於回填夯實向不予重視，其因此而產生之災損與民怨，實屬罄竹難書(吳淵洵等人，2002)。有鑑於此，使用具有自流性、免夯實、高強度、低沈陷等優良工程性質之控制性低強度材料(controlled low strength material, CLSM亦稱流填料，flowable fill)，取代傳統天然砂石級配回填料，可確實提昇填土品質。改善管溝回填品質不良之弊病，若以垃圾焚化底渣作為CLSM之骨材，更可具有減少廢棄物、節省天然砂石資源之環保生態價值。由於底渣之水泥拌和物具有緩凝現象，無法符合都會地區管溝回填之時效性要求，因此研討底渣拌製之CLSM緩凝改善對策，使之適用於都會地區管溝之回填

實為目前底渣再利用亟須探討之重要主題。

鑑於垃圾焚化底渣資源化處理極其重要，而都會地區保障管溝回填工程品質工法及砂石替代材料之發展亦刻不容緩。本研究遂以實驗室試驗之方式，探討垃圾底渣流填料之早強可能性，以期此一具有環保價值之工法得予實際應用，除可紓解國內垃圾焚化底渣處理困難之窘境，減少天然砂石之耗用，亦可提昇都會地區管溝回填之工程品質。

本研究以新店垃圾焚化廠之都市垃圾焚化底渣為骨材並添加相關摻料於實驗室，試驗不同配比拌製之流填料，以試驗方式觀察不同配比底渣流填料試體其工程性質之變化，探討此種材料作為都會地區管溝回填應用之可行性與適用性，並提出最佳配比建議。

## 三、研究計畫與試驗流程

本研究之目的為探討底渣流填料之早強可能性及其相關工程性質，因此研究之執行主要係以添加化學摻料之方式觀察不同配比之試體其流動性、早強性、速凝性之變化及其對單軸壓縮強度之影響，從而驗證底渣於都市管溝回填工程應用之可行性。

### 3.1 試驗項目與方法

試驗之進行首先為底渣之基本物理性質觀察並予以分類；其次進行底渣流填料之配比設計試驗，添加不同化學摻料拌製各種不同配比之試體，進行流度、泌水率、單軸壓縮強度之觀察；最後針對試驗結果予以分析比較。相關之試驗項目與參考試驗規範說明如次：

1. 基本物理性質試驗：包括比重(ASTM D854-83)與粒徑分佈(ASTM D452-85)等。
2. 底渣流填料之配比設計：以流度為控制變數，針對不同灰水比及水固比，添加不同比例之減水劑、早強劑及速凝劑，試驗項目包括流動性(ASTM D6103)、泌水率(ASTM C940) 、單位重以及單軸壓縮強度(ASTM D2938)。

### 3.2 試驗材料

#### 3.2.1 底渣

本研究所使用之底渣係經國賓資源處理廠前處理之北區新店焚化廠之底渣。試樣顏色呈灰黑色且具有腐臭味。烘乾後之底渣則呈灰白色，並具團塊的現象，惟經由手或振動篩即可容易將部份團塊分散。

#### 3.2.2 固化劑

本研究所使用之固化劑為台灣水泥公司所生產之波特蘭第 I 型水泥，並符合CNS 61-R2001之規定。

#### 3.2.3 高性能減水劑

高性能減水劑(HI CON SPF)，屬於奈磺酸系高分子複合有機化學摻料，符合ASTM C 494規範。由於具高分散性及低起泡性，對水泥粒子具有分散功能，有效的大幅降低水灰比，減少泌水現象，保持混凝土體積之穩定性，提高混凝土強度。

依據材料廠商之建議，減水劑添加量為水泥量之 0.75～2.4%，可產生達 12～30%之高減水率，並使水灰比減低至 0.25 以下，而工作度仍維持不變，且每增添 0.1%約可提高 2cm 之坍度(啟欣股份有限公司，2006)。

#### 3.2.4 早強劑

所使用之早強劑屬無機鹽類成份的硫酸鈉，與水泥水化時產生的$Ca(OH)_2$可發生下列反應：

$Na_2SO_4+Ca(OH)_2+2H_2O \rightarrow CaSO_4 \cdot 2H_2O+2NaOH$

所生成的二水石膏顆粒細小，較水泥熟料中原有的二水石膏更快地參加水化反應：

$CaSO_4 \cdot 2H_2O+C_3A+12H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 12H_2O$

使水化產物硫鋁酸鈣更快地生成，從而加快了水泥的水化硬化速度。它的1天強度提高尤其明顯。由於早期水化物結構形成較快，結構緻密程度較差一些，因而後期28天強度會略有降低。早期強度增加愈快，後期強度就愈易受到影響，因而硫酸鈉摻量應有一個最佳控制量。一般在水泥用量之1%～3%之間，摻量低於1%，早強作用不明顯，摻量太大則後期強度損失較大，故一般在1.5%較為適宜。

硫酸鈉早強劑在水化反應中，由於生成了NaOH，而使鹼度有所提高，這對摻有火山灰和礦渣的水泥及摻有活性超細摻合料的混凝土早強作用更為明顯。但同時對於活性骨料來說也容易導致鹼骨材反應。

硫酸鈉在混凝土中使用，當摻量過大或養護條件不好時，容易在混凝土表面產生「返鹼」現象，即在混凝土表面析出一層毛茸狀的$Ca(OH)_2$細小晶體，而影響混凝土表面的光澤程度，也不利於表面進一步裝飾處理。

### 3.2.5 速凝劑

速凝劑最主要之目的是將水泥化合物中之矽酸三鈣與矽酸二鈣的反應提前產生，俾使早期強度發展可以於短時間需求內達到一定的目標。

速凝劑的使用會同時加速漿體的初凝與終凝時間，欲提前多少端看添加量而定。一般而言，添加量在水泥用量之0.5%～5%時，凝結時間可加速數分鐘至數小時不等(啟欣股份有限公司，2006)。

使用速凝劑可促進早期強度的發展，然而提昇多少則視配比設計、溫、溼度、養護條件、水灰比及水泥種類等而定；不過可確定的是，速凝劑對於所有的水泥均有效，但添加過量仍會對強度造成折損(啟欣股份有限公司，2006)。

### 3.2.6 化學摻料拌合順序

本研究之底渣流填料添加3種化學摻料，以流度為控制因素，必須注意摻料之添加順序。減水劑與早強劑在底渣與水泥乾拌後添加，再加入所需拌和水，因減水劑與早強劑可提高工作性並同時減少拌和水用量；速凝劑則於底渣流填料拌製完成灌模前添加。

## 3.3 底渣流填料之配比設計試驗

### 3.3.1 配比計算

底渣流填料之配比設計其添加的材料數量乃遵循下列公式計算：

灰水比(C/W)＝水泥重/水重 (3-1)

水固比(W/S)＝水重/固體重 (3-2)

固體重＝水泥重+底渣重 (3-3)

化學摻料＝水泥重之 1~3% (3-4)

配比設計流程以下例說明：

(1) 假設控制參數(C/W＝0.3，W/S＝0.2)。
(2) 依所需澆置試體量假設固體重1000g。
(3) 將假設固體重代入公式 3-2 得出水重200g。
(4) 將水重代回公式 3-1 得出所需水泥重60g。
(5) 再將水泥重代回公式 3-3 可得到底渣重 940g。
(6) 最後依水泥重換算出所需化學摻料

的重量，例如 3%即為 18g。

故底渣流填料 C/W＝0.3，W/S＝0.2 所需各材料之添加量即可求得。

### 3.3.2 流動性

依照 ASTM D 6103 之要求，以 7.5cmϕ×15cmH 圓柱鋼模量測其流動性。將烘乾之底渣與水泥量於拌和盆內先行乾拌和均勻後，依照所需實驗配比加入適當拌和水調勻。

1. 以濕抹布將鋼模內側壁潤濕並置於鋼鈑上，以手固定鋼模，防止鋼模底部滲水。
2. 將拌和好流填料倒入鋼模內，直至填滿為止。
3. 以鏝刀刮平頂部，並立即以穩定的速度將鋼模垂直向上提起，其速度約為 5±2 秒內 30 公分。
4. 以游標卡尺量測流填料之流度值。流度值即為流填料流動範圍之直徑。

### 3.3.3 泌水率試驗

將烘乾之底渣與水泥量於拌和盆內先行乾拌和均勻後，依照所需實驗配比加入適當拌合水調勻。

1. 首先將銅模底部以橡皮套封住，倒入已拌和好之流填料直到填滿為止，以鏝刀依試體高度將頂部刮平，靜置 24 小時。
2. 將試體由銅模內以頂土器頂出，以游標卡尺量測試體高度並記錄之。
3. 泌水率為泌水高度（試體之高度與銅模之高度差）與銅模高度之比值。

### 3.3.4 單軸壓縮試驗

本研究之試驗儀器為計測企業有限公司製造之單軸壓縮試驗試驗儀。主要包括壓力機、荷重儀表與垂直應變計等。試驗速率為電子調速，本研究是以 1%/min 之加載速率進行試驗。

1. 依照各種配比拌和後，澆置於銅模（3.5cmϕ×7cm）內，靜置 24 小時，再以頂土器將試樣小心取出後編號歸類。
2. 依照齡期將試體取出，置於試驗儀器上進行單軸壓縮試驗。

## 四、試驗結果與分析

本研究以試驗方式探討底渣流填料應用於都市管溝回填之可行性。為求底渣之最大資源化再利用，試驗係以全底渣配合添加各種化學摻料之方式進行，重點探討底渣流填料之早強可能性及工程性質，依實際工程考量求出適當且合理之配比設計並提出配比建議。

### 4.1 基本性質試驗結果

底渣試樣之比重平均值為 2.62。粒徑分析結果如圖 1 所示，底渣之均勻係數(Cu)為 11.33、曲率係數(Cd)為 1.36、通過 200 號篩之細料僅為 6.82%且不具塑性，故底渣試樣應屬略含粉土之優良級配砂土 SW-SM (統一土壤分類法，USCS)。

### 4.2 配比設計試驗結果

底渣流填料之配比設計目標為探討底渣、水泥及化學摻料之適當比例。觀察各種拌合料之早強性質及速凝機制，以評估其於都市管溝回填應用之可行性。為簡化各種變異因素對流填料之影響，本研究以流度為控制因素，比較各不同配比之早強工程性質。

#### 4.2.1 流動性

如圖 2 所示，底渣流填料與前人研究之一般流填料類似，其流度隨水固比及灰水比之增加而增加，惟其中以水固比之影響較為明顯(黃政昭，2005；蔡慕凡，2003；李銘哲，2000)。良好流動性對工作性極具助益，然而拌和水較多亦容易造成粒料析離、泌水量增加，影響流填料之品質，故流度應於符合強度及施工性能要求之前提

下，降低至最小限度。

依據 ASTM D 6103 建議，適當之流度值應介於 15cm 至 20cm 之間。試驗結果顯示，底渣流填料當水固比為 0.35～0.40，灰水比為 0.2～0.3 時，具有較理想之流度值。

### 4.2.2 早強性

近年來隨著國民生活水準的提昇，許多維繫民生之重要管線如自來水管、瓦斯、電信、電力與下水道設施等，紛紛地下化發展且多埋設於道路下方。由於民生管線埋設維修等問題，使得道路往往於鋪築過後仍須面臨再開挖回填的情況。重複挖填以及人為施工不當等因素之影響，常造成道路品質低劣嚴重危及道路交通安全。考量管線施工地點多涉及交通動線之通暢，故都會地區道路挖掘回填作業另具有急切之時效性，因此本研究針對管溝回填之施工需求，進行流填料早強性質之研究。

依據前人之探討(李銘哲，1999；陳雨音，2002)，應用於管溝回填之流填料必須兼顧強度與時間之配合，其基本要求為在澆置 4～6 小時內，單軸強度應達 100kPa 以上。一般型底渣流填料之代表性試驗結果如圖 3 所示，其單軸強度($q_u$)與灰水比、水固比之關係與黃政昭(2005)所觀察者類似。於灰水比 0.2～0.5、水固比 0.35～0.45 時，其 $q_u$ 值皆隨水固比之降低、灰水比之增加而增加，惟齡期 1 天低於 100kPa，顯示底渣流填料之早期強度甚低，確實無法符合都會地區管溝回填之應用需求。由於底渣流填料具有緩凝性質且含水量過高，導致早強性不佳，因此必須添加化學摻料以提昇其早強性能。考量流填料之應用特點為其流動性，因此本研究以控制流度為前提，探討不同化學摻料包含減水劑、早強劑及速凝劑等對於增加底渣流填料早期強度之可能性。又因考量管溝再開挖之需要，因此底渣流填料之後期強度亦必須加以限制。

### 4.2.3 減水劑與早強性之關係

圖 4 所示為不同減水劑含量對具有相同流度之底渣流填料之強度影響代表性結果。由圖可知，各試體之初期強度均隨齡期之增加而增加，且其強度均於 24 小時內急遽增加惟齡期超過 1 天後，強度增加之趨勢即逐漸減緩並於 7 天後產生強度折減之現象。試驗結果亦顯示，不論灰水比之大小，使用不同含量之減水劑對於早強性之影響甚微。長期強度之發展亦與減水劑含量並無規則性之關聯。

### 4.2.4 早強劑與早強性之關係

早強劑對底渣流填料早強性之影響代表性結果如圖 5 所示。試驗結果顯示使用少量早強劑對於早強性之提昇即產生具體之影響且水泥量愈低，此種關係愈為明顯，惟當早強劑用量超過 2%以後，早強劑用量與早強性之關係即不明顯。由圖可知，於一般流度之限制下，使用早強劑 1%即可使底渣流填料之 6 小時強度達 100kPa 以上，惟如欲使其 4 小時強度達到目標值，則依據試驗結果，以增加水泥量之方式較為適宜。

### 4.2.5 用水量與早強性之關係

圖 6 為於一定流度之限制下，使用定量水泥、不同減水劑時，各試體之強度變化。由圖可知，在相同流度之前提下，增加減水劑，減少用水量並相對增加灰水比、降低水固比。試驗結果顯示使用減水劑雖可降低用水量但對底渣流填料之早強性影響仍然有限。各不同減水劑含量之試體其早期強度多大致相同，而長期強度則與減水劑用量並未呈現規則性之關係。造成此種現象之原因推測應係在維持一定流度之要求下，較高之用水量限制了早期強度之發展，而後期強度則在早強劑之影響

下呈現不規則之變化。

### 4.2.6 長期強度之變化

早強型底渣流填料各配比試體之長期強度代表性結果如圖 7 所示。水泥用量較低之試體其28天強度與7天強度均呈現折減之現象，且水泥用量愈低，早強劑用量愈高，此種情形愈為明顯。本研究使用之早強劑為硫酸鈉，在水泥初期硬化時能與氫氧化鈣作用，促進水泥水化故具有早強作用，惟於較長時時間之後，水泥水化作用趨緩，且底渣流填料含有泥質及有機物等不良雜質均可能影響其長期強度之發展，惟依據試驗結果，即使在低水泥量之情形下，多數試體之 28 天強度均超過最小設計目標值(600kPa)，故配比設計所得結果應屬可行。由於研究時程之限制，早強型底渣流填料之長期強度變化仍待後續研究進一步探討。

## 4.3 試驗結果之統計分析

由試驗結果可知，影響焚化底渣流填料早強性之試驗參數眾多，其散佈圖形狀之間的因果關係亦未顯示規則性之趨勢。為探討各試驗參數與強度之相關性，本研究以商業軟體SPSS及Excel執行複迴歸分析，相關細節說明如次。

### 4.3.1 迴歸模型之檢定

迴歸分析是在討論變數間的關係，並根據一些相關的理論建立預測模型，進而討論其重要的統計推論。在迴歸分析中，必有一因變數稱為被解釋變數或被預測變數，一般以 y 表示；另可能有數個自變數，又稱為獨立變數或預測變數或解釋變數，一般以 $x_i$ 表示。如果自變數只有一個，稱為簡單迴歸；若自變數有二個或二個以上者，則稱為複迴歸。另外，若變數之間具有統計關係，則進行迴歸分析的目的即在於找出一適當的數學方程式以表示其關係，此方程式謂之迴歸方程式(方世榮，1998；林惠玲、陳正倉，2002)。

評定一個迴歸模式的實用性及相關程度解釋能力或配適度能力之優劣，主要可由三個的統計量來判斷，包括判定係數($R^2$)、相關係數(R)與 F 值檢定，每一種方法各有其特別的涵意及適用情況。一般而言，在表示一迴歸模型及其估計結果與相關的統計量，皆有一定型式。以下即針對三種主要的統計量分析介紹(方世榮，1998；林惠玲、陳正倉，2002)。

1.F 值檢定(顯著性檢定)

複迴歸分析可利用 F 檢定探討迴歸方程式所有自變數(Xi)對依變數(Y)是否具有聯合解釋能力，並具有方程式關係：

$E(Y)=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\cdots+\beta_kX_k$，檢定該迴歸方程式是否可被接受時，虛無假設與對立假設分別為：

$H_0$：迴歸方程式無解釋能力 $(\beta_1=\beta_2=\ldots=\beta_k=0)$

$H_1$：迴歸方程式有解釋能力 ($\beta_i$=不全為 0)

虛無假設 $H_0$ 為全體迴歸係數均為 0，表示迴歸方程式的解釋變數無聯合解釋能力；而 $H_1$ 為至少有一個迴歸係數不為 0，或迴歸方程式的解釋變數有聯合解釋能力(方世榮，1998；林惠玲、陳正倉，2002)。利用 F 統計檢定量來做檢定：

$$F=\frac{MSR}{MSE}\sim F_{k,n-k-1}$$

檢定法則：

①$F > F_{k,n-k-1,\alpha}$，則拒絕 $H_0$。

②$F \leqq F_{k,n-k-1,\alpha}$，則接受 $H_0$。

拒絕 $H_0$ 表示迴歸方程式的自變數對依變數具有解釋能力，迴歸模型可接受；反之，若接受 $H_0$，則表示迴歸方程式不具解釋能力。

2.判定係數($R^2$)

前述 F 值檢定可知迴歸模式其統計是否具有顯著性，然而對於顯著關係間的強度大小或迴歸模型對應於相關資料的配適

程度(解釋能力)，則可利用判定係數 $R^2$(coefficient of determination)加以判斷。判定係數介於 0 與 1 之間，當比值愈接近 1 時，表示迴歸關係愈強或迴歸模型的解釋能力愈高(方世榮，1998；林惠玲、陳正倉，2002)。

3.相關係數(R)

探討變數間的關係，除了前述的迴歸分析外，另一種方法即是相關分析(correlation analysis)。迴歸分析為尋求因變數與自變數之間關係的數學方程式，而相關分析則在探討各變數之間的相關程度及相關方向。因此，用以衡量相關程度大小與方向的數量稱為相關係數。

### 4.3.2 減水劑對早強性影響之統計分析

探討不同減水劑含量對強度之影響，針對其試驗結果執行迴歸分析。表 1～表 4 顯示試驗參數為灰水比、水固比及齡期時以強迫進入變數法(enter)進行複迴歸分析之統計結果。由表可知上述三個變數僅可解釋強度 43.9%之變異量。複迴歸變異數分析(analysis of variancc , ANOVA)F 值檢定顯示整體而言，強度與灰水比、水固比及齡期具有顯著之線性關係。然而檢定個別試驗參數與強度之迴歸關係時則發現僅有齡期具有顯著之預測力。此組試驗是針對不同比例之減水劑對強度之影響，整體顯示結果其對試體強度並無太大影響，齡期為顯著影響因子。

統計迴歸預測模式如下：

1.齡期 4 小時

$q_u=347.95+125.83x_1-1205.29x_2$

式中：

$q_u$ =單軸壓縮強度(kPa)

$x_1$=灰水比

$x_2$=水固比

(1)F 值檢定

檢定統計量 F 值=45.80，在顯著水準 $\alpha=0.05$ 下，$F(2,9)=4.26$。

由於 F 值大於 $F_\alpha$，因此結論拒絕 $H_0$，亦即表示強度與其二個變數 $x_1$ 及 $x_2$ 具有顯著的線性關係，可利用迴歸估計方程式來預測強度。

(2)判定係數 $R^2$

判定係數 $R^2=0.91$，表示在控制條件下有 91%試驗參數強度關係，觀察資料對迴歸模型的解釋能力極佳。

2.齡期 6 小時：

$q_u =574.91+193.35x_1-1878.82x_2$

(1)F 值檢定

檢定統計量 F 值=28.78，在顯著水準 $\alpha=0.05$ 下，$F(2,9)=4.26$。

由於 F 值大於 $F_\alpha$，因此結論拒絕 $H_0$，亦即表示強度與其二個變數 $x_1$ 及 $x_2$ 具有顯著的線性關係，可利用迴歸估計方程式來預測強度。

(2)判定係數 $R^2$

判定係數 $R^2=0.86$，表示在控制條件下有 86%試驗參數強度關係，觀察資料對迴歸模型的解釋能力極佳。

3.齡期 1 天：

$q_u =5758.54+1401.53x_1-19125.84x_2$

(1)F 值檢定

檢定統計量 F 值=50.73，在顯著水準 $\alpha=0.05$ 下，$F(2,9)=4.26$。

由於 F 值大於 $F_\alpha$，因此結論拒絕 $H_0$，亦即表示強度與其二個變數 $x_1$ 及 $x_2$ 具有顯著的線性關係，可利用迴歸估計方程式來預測強度。

(2)判定係數 $R^2$

判定係數 $R^2=0.92$，表示在控制條件下有 92%試驗參數強度關係，觀察資料對迴歸模型的解釋能力極佳。

4.齡期 7 天：

$q_u =9106.71+3308.09x_1-32543.50x_2$

(1)F 值檢定

檢定統計量 F 值=38.22，在顯著水準 $\alpha=0.05$ 下，$F(2,9)=4.26$。

由於 F 值大於 $F_\alpha$，因此結論拒絕 $H_0$，亦即表示強度與其二個變數 $x_1$ 及 $x_2$ 具有顯著的線性關係，可利用迴歸估計方程式來預測強度。

(2)判定係數 $R^2$

判定係數 $R^2=0.89$，表示在控制條件下有 89%試驗參數強度關係，觀察資料對迴歸模型的解釋能力極佳。

5.齡期 28 天：

$q_u=997.79+5151.65x_1-7519.23x_2$

(1)F 值檢定

檢定統計量 F 值=89.60，在顯著水準 $\alpha=0.05$ 下，$F(2,9)=4.26$。

由於 F 值大於 $F_\alpha$，因此結論拒絕 $H_0$，亦即表示強度與其二個變數 $x_1$ 及 $x_2$ 具有顯著的線性關係，可利用迴歸估計方程式來預測強度。

(2)判定係數 $R^2$

判定係數 $R^2=0.95$，表示在控制條件下有 95%試驗參數強度關係，觀察資料對迴歸模型的解釋能力極佳。

### 4.3.3 早強劑對早強性影響之統計分析

本節所討論者為早強劑與強度關係之相關分析與迴歸結果(表 5～表 8)。由表可知，添加早強劑後，灰水比、齡期及早強劑含量可解釋 76.9%之變異量。ANOVA F 值檢定顯示，整體而言，強度與灰水比、齡期及早強劑含量具有顯著之線性關係。檢定個別試驗參數與強度之迴歸關係時則發現以齡期預測強度具有 44.5%的解釋能力，以早強劑含量預測強度具有 26.1%的解釋力，而以灰水比預測強度則具有 69.3%的解釋力，顯示灰水比解釋力較其他兩者更具有統計上的意義。此組試驗是針對不同比例之早強劑對強度之影響，整體顯示結果其對試體強度均有影響，而灰水比為最顯著之影響因子。

根據 SPSS 之統計結果，減水劑對於早強性並無顯著之影響；而添加早強劑則對於早強性則具有較顯著之影響。

統計迴歸預測模式如下：

1.齡期 4 小時：

$q_u=1077.89+45.43x_1-3710.49x_2$

(1)F 值檢定

檢定統計量 F 值=8.93，在顯著水準 $\alpha=0.05$ 下，$F(2,9)=4.26$。

由於 F 值大於 $F_\alpha$，因此結論拒絕 $H_0$，亦即表示強度與其二個變數 $x_1$ 及 $x_2$ 具有顯著的線性關係，可利用迴歸估計方程式來預測強度。

(2)判定係數 $R^2$

判定係數 $R^2=0.66$，表示在控制條件下有 66%試驗參數強度關係，觀察資料對迴歸模型的解釋能力尚可。

2.齡期 6 小時：

$q_u=733.58+235.43x_1-2507.49x_2$

(1)F 值檢定

檢定統計量 F 值=11.42，在顯著水準 $\alpha=0.05$ 下，$F(2,9)=4.26$。

由於 F 值大於 $F_\alpha$，因此結論拒絕 $H_0$，亦即表示強度與其二個變數 $x_1$ 及 $x_2$ 具有顯著的線性關係，可利用迴歸估計方程式來預測強度。

(2)判定係數 $R^2$

判定係數 $R^2=0.72$，表示在控制條件下有 72%試驗參數強度關係，觀察資料對迴歸模型的解釋能力極佳。

3.齡期 1 天：

$q_u=9728.08+1712.91x_1-34962.31x_2$

(1)F 值檢定

檢定統計量 F 值=13.41，在顯著水準 $\alpha=0.05$ 下，$F(2,9)=4.26$。

由於 F 值大於 $F_\alpha$，因此結論拒絕 $H_0$，亦即表示強度與其二個變數 $x_1$ 及 $x_2$ 具有顯著的線性關係，可利用迴歸估計方程式

來預測強度。

(2)判定係數 $R^2$

判定係數 $R^2=0.75$，表示在控制條件下有 75%試驗參數強度關係，觀察資料對迴歸模型的解釋能力極佳。

4.齡期 7 天：

$q_u=2859.79+4820.95x_1-12470.04x_2$

(1)F 值檢定

檢定統計量 F 值=51.64，在顯著水準 $\alpha=0.05$ 下，$F(2,9)=4.26$。

由於 F 值大於 $F_\alpha$，因此結論拒絕 $H_0$，亦即表示強度與其二個變數 $x_1$ 及 $x_2$ 具有顯著的線性關係，可利用迴歸估計方程式來預測強度。

(2)判定係數 $R^2$

判定係數 $R^2=0.92$，表示在控制條件下有 92%試驗參數強度關係，觀察資料對迴歸模型的解釋能力極佳。

5.齡期 28 天：

$q_u=-3611.17+6984.82x_1+6388.71x_2$

(1)F 值檢定

檢定統計量 F 值=62.92，在顯著水準 $\alpha=0.05$ 下，$F(2,9)=4.26$。

由於 F 值大於 $F_\alpha$，因此結論拒絕 $H_0$，亦即表示強度與其二個變數 $x_1$ 及 $x_2$ 具有顯著的線性關係，可利用迴歸估計方程式來預測強度。

(2)判定係數 $R^2$

判定係數 $R^2=0.93$，表示在控制條件下有 93%試驗參數強度關係，觀察資料對迴歸模型的解釋能力極佳。

## 五、結論與建議

本研究以試驗方式探討底渣流填料應用於都市管溝回填工程之可行性，藉以提昇底渣資源化之再利用。研究之主要目的為評估垃圾焚化底渣流填料之早強性，以添加化學摻料之方式，探討合理之設計配比及其工程性質。依據研究成果可獲致之結論與建議如次。

### 5.1 結論

1. 底渣流填料建議之流度與一般流填料所表現者類似，隨水固比及灰水比之增加而增加，且以水固比之影響較為明顯。底渣流填料之水固比為 0.35～0.40，灰水比為 0.2～0.3 時可具有適當之流度。
2. 底渣流填料之強度隨灰水比之增加、水固比之降低而增加，惟因其具有緩凝性質，齡期 1 天之試體其強度均較低，無法符合都會地區管溝回填之時效要求。
3. 添加減水劑、速凝劑及早強劑均可改善底渣流填料之早強性，惟依據試驗結果之觀察及統計分析趨勢之判斷，三種摻料之中以早強劑對於早強性之影響最為顯著。於標準流度之限制下，早強劑之建議用量為 1%。超過此限值之後，改善早強性則以增加水泥量之方式較為適宜。
4. 早強型底渣流填料各配比之長期強度均呈現折減之現象，且水泥用量愈低、早強劑用量愈高，此種情形愈為明顯，其原因應與水泥水化作用趨緩及底渣包含雜質有關。由於多數試體之 28 天強度均達設計目標值，故配比設計所得結果應屬可行。

### 5.2 建議

1. 本研究所探討者為規模較小之實驗室試驗，且底渣試樣料源單純。欲推廣早強型底渣流填料之實際應用，未來應再推行現地大型澆置試驗，檢測現地工程性質，並與實驗室參數比對，確認底渣流填料作為都會地區管溝回填之最佳配比設計。
2. 底渣資源化應用對於紓解我國垃圾焚化底渣處理之困境極為重要，以其拌製流填料並用之於管溝回填不僅可以解

決底渣處理問題亦可改善管溝回填品質。然而底渣成份複雜且可能包含有害物質，鑑於流填料之水泥用量不高，固化能力偏低，未來應就底渣流填料滲出水析出成份之環境相容性進行完整探討，以確認其安全性。

## 六、參考文獻

[1] 方世榮（1998），「統計學導論(三版)」，華泰書局。

[2] 行政院環保署網站(2005)，http://ivy3.epa.gov.tw/swims/(2006/08/24 瀏覽)。

[3] 台灣營建研究院（2003），「CLSM 材料規範」，財團法人台灣營建研究院。

[4] 啟欣（2006)，「減水劑及速凝劑之產品配比建議說明」，啟欣股份有限公司，台中。

[5] 江少鋒（1995），「都市焚化灰燼作為水泥混凝土細骨材之可行性」，碩士論文，中央大學土木工程學研究所，中壢。

[6] 李釗、江少鋒、郭文田（1997），「垃圾焚化灰渣作為混凝土細骨材之可行性研究」，中國環境工程學刊，第七卷，第三期，第289-296頁。

[7] 李建中、李釗、鄭清江、何啟華（1996），「垃圾焚化灰燼之大地工程特性」，中國土木水利工程學刊，第八卷，第三期，第 397-404 頁。

[8] 李銘哲（2000），「自流性填方材料之工程性質及可行性探討」，碩士論文，中華大學土木工程系，新竹。

[9] 李維峰、柴希文、吳淵洵、謝啟萬（2002）「控制性低強度材料於土木工程應用之研究」，財團法人台灣營建研究院，內政部營建署委託。

[10] 李公哲、吳淵洵、邱垂德（2004），「廢棄物焚化灰渣材料化技術研究（第二年）」，台灣大學環境工程研究所，行政院環境保護署委託。

[11] 吳淵洵、陳盟文（2004），「垃圾焚化底渣流填料於管溝回填之應用」，第六屆鋪面材料再生學術研討會論文集，高雄。

[12] 吳盛昆、廖吳章、林志棟（2000），「挖掘道路回填夯實之探討」，台灣公路工程，第二十六卷，第七期，第 11-35 頁。

[13] 吳振福（1997)，「碎石級配料濕陷機制之探討」，碩士論文，中華大學土木工程系，新竹。

[14] 林育丞（2003），「垃圾焚化底渣與水泥拌合後之潛在問題探討」，碩士論文，中央大學土木工程研究所，中壢。

[15] 林惠玲、陳正倉（2002），「應用統計學(二版)」，雙葉書廊有限公司。

[16] 胡志誠（2004），「焚化廠底灰應用於工程回填材料之環境安全性研究」，碩士論文，台灣大學土木工程學研究所，台北。

[17] 孫世勤（2003），「垃圾焚化底渣初級篩分資源再利用廠興建工程規劃、設計及監造計畫」，財團法人台灣營建研究院，行政院環境保護署委託。

[18] 陳雨音（2002），「結構與管溝回填替代工法之探討」，碩士論文，中華大學土木工程系，新竹。

[19] 陳仙州（2002），「CLSM 應用於道路回填工程之研究及工地驗證（初期成果報告）（一）」，台灣公路工程，第二十八卷，第七期，第 39-48 頁。

[20] 陳仙州（2002），「CLSM 應用於道路回填工程之研究及工地驗證（初期成果報告）（二）」，台灣公路工程，第二十八卷，第八期，第 24-45 頁。

[21] 陳仙州（2002），「CLSM 應用於道路回填工程之研究及工地驗證（初期成

果報告）（三）」，台灣公路工程，第二十八卷，第九期，第 40-56 頁。

[22] 曹有財（2002），「控制性低強度材料於道路管溝修護之研究」，碩士論文，台北科技大學土木與防災技術研究所，台北。

[23] 張蕙蘭（2003），「國外焚化底渣再利用介紹」，永續產業發展雙月刊，第十二期，第 55-64 頁。

[24] 黃政昭（2005），「垃圾焚化底渣應用於填方工程之研究」，碩士論文，中華大學土木工程系，新竹。

[25] 葉祥春（2003），「垃圾焚化底爐底碴應用於道路基底層之研究」，碩士論文，成功大學土木工程研究所，台南。

[26] 雷揚中（2004），「焚化爐底碴應用於道路工程之研究」，公共工程品質管理系列叢書，瀝青混凝土材料特性系列專輯（二十九），中央大學土木工程研究所，中壢。

[27] Gress, D., Zhang, X., Tarr, S., Pazienza, I., and Eighmy, T., (1992),” Physical and Environmental Properties of Asphalt-Amended Bottom Ash”, Transportation Research Record 1345, pp. 10-18.

[28] Lee, M. T. and Nicholson, P. G., (1997), “An Engineering Test Program of MSW Ash Mixed with Quarry Tailings Use as A Landfill Construction Material”, Testing Soil Mixed with Waste or Recycled Materials, ASTM STP 1275, Mark A. Wasemiller and Keith B. Hoddinott, Eds., ASTM, pp. 205-218.

[29] Pandeline, D. A., Cosention, P. J., Kalajian, E. H., and Chavez, M. F., (1996), ” Shear and Deformation Characteristics of Municipal Waste Combustor Bottom Ash for Highway Applications”, Transportation Research Record 1577, pp. 101-108.

[30] Pecqueur, G., Crignon, C., Quenee, B., (2001), “Behaviour of Cement-treated MSWI Bottom Ash,” Waste Management Vol. 21, pp. 229 - 233.

[31] Rivard-Lentz, D. J., Sweeney, L. R., Demars, K. R., (1997), “Incinerator Bottom Ash as A Soil Substitute: Physical and Chemical Behavior”, Testing Soil Mixed with Waste or Recycled Materials, ASTM STP 1275, Mark A. Wasemiller and Keith B. Hoddinott, Eds., ASTM, pp. 246-262.

[32] Uchida, T., Hirao, T., Shimaoka, T., Miyawaki, K., Hanashima, M., (2004), “Application of Bottom Ash as Road Construction Materials”, 台北縣焚化灰渣再利用國際研討會論文集，台北。

表 1 輸入/移除之變數(減水劑)

| 模式 | 輸入之變數 | 移除之變數 | 分析方法 |
|---|---|---|---|
| 1 | 齡期、水固比、灰水比 | 無 | 強迫進入變數法 |

a.所有要求輸入之變數
b.依變數：強度

表 2 模式摘要(減水劑)

| 模式 | 相關係數 (R) | 判定係數 ($R^2$) | 調整 $R^2$ | 估計標準誤差 |
|---|---|---|---|---|
| 1 | 0.662 | 0.439 | 0.409 | 1144.57230 |

a.預測變數：(常數)、齡期、水固比、灰水比
b.依變數：強度

表 3 變異數分析(減水劑)

| 模式 | 平方和 | 自由度 | 平均平方和 | F 檢定 | 顯著性 |
|---|---|---|---|---|---|
| 迴歸 | 57320230.689 | 3 | 19106743.56 | 14.585 | 0.000 |
| 殘差 | 73362561.740 | 56 | 1310045.745 | | |
| 總和 | 130682792.429 | 59 | | | |

a.預測變數(常數)、齡期、水固比、灰水比
b.依變數：強度

表 4 統計分析結果(減水劑)

| 模式 | 未標準化係數 | | 標準化係數 | t | 顯著性 |
|---|---|---|---|---|---|
| | B 之估計值 | 標準誤差 | Beta 分配 | | |
| Const | 2934.122 | 7687.220 | | 0.382 | 0.704 |
| C/W | 2036.091 | 1756.120 | 0.358 | 1.159 | 0.251 |
| W/S | -12454.536 | 25343.518 | -0.152 | -0.491 | 0.625 |
| Age | 2.477 | 0.577 | 0.430 | 4.295 | 0.000 |

a. 依變數：強度

表 5 輸入/移除之變數(早強劑)

| 模式 | 輸入之變數 | 移除之變數 | 分析方法 |
|---|---|---|---|
| 1 | 齡期、早強劑、灰水比 | 無 | 強迫進入變數法 |

a.所有要求輸入之變數

b.依變數：強度

表 6 模式摘要(早強劑)

| 模式 | 相關係數 (R) | 判定係數 ($R^2$) | 調整 $R^2$ | 估計標準誤差 |
|---|---|---|---|---|
| 1 | 0.887 | 0.769 | 0.735 | 54.50886 |

a.預測變數：常數、齡期、早強劑、灰水比

b.依變數：強度

表 7 變異數分析(早強劑)

| 模式 | 平方和 | 自由度 | 平均平方和 | F 檢定 | 顯著性 |
|---|---|---|---|---|---|
| 迴歸 | 198111.666 | 3 | 66037.222 | 22.226 | 0.000 |
| 殘差 | 59424.323 | 20 | 2971.216 | | |
| 總和 | 257535.989 | 23 | | | |

a.預測變數：(常數)、齡期、早強劑、灰水比

b.依變數：強度

表 8 統計分析結果(早強劑)

| 模式 | 未標準化係數 | | 標準化係數 | t | 顯著性 |
|---|---|---|---|---|---|
| | B 之估計值 | 標準誤差 | Beta 分配 | | |
| Const | -299.903 | 67.612 | | -4.436 | 0.000 |
| C/W | 292.856 | 45.469 | 0.693 | 6.441 | 0.000 |
| W/S | 24.228 | 9.971 | 0.261 | 2.430 | 0.025 |
| Age | 46.073 | 11.127 | 0.445 | 4.141 | 0.001 |

a.依變數：強度

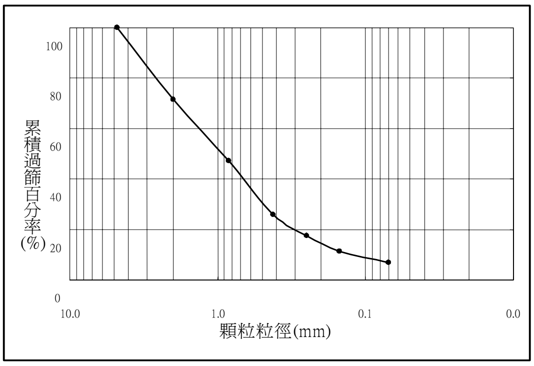

圖 1 焚化底渣之粒徑分佈

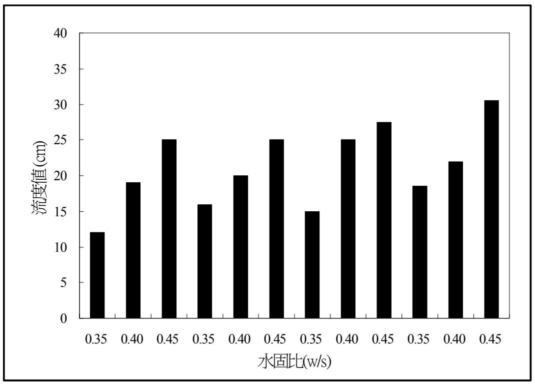

圖2 底渣流填料之流度值與各控制參數之關係

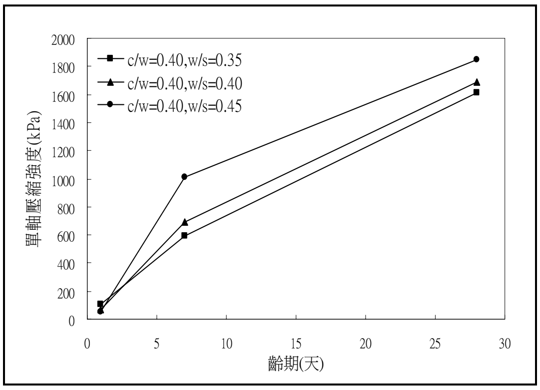

圖 3 底渣流填料之單軸壓縮強度與水固比及齡期之關係 (灰水比=0.40)

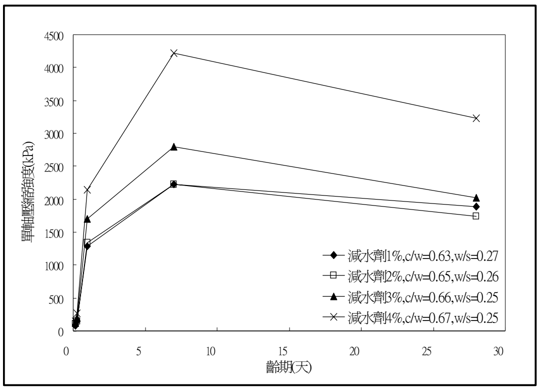

圖 4 底渣流填料之單軸壓縮強度與減水劑添加量之關係

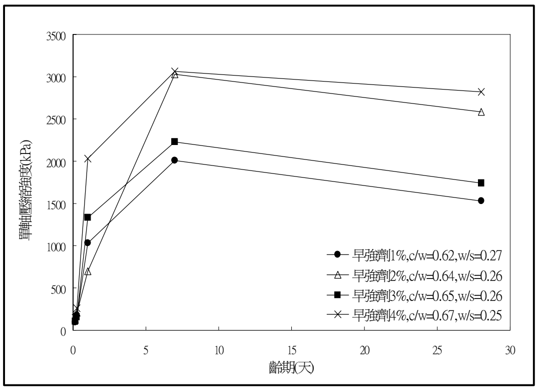

圖 5 底渣流填料之單軸壓縮強度與早強劑添加量之關係

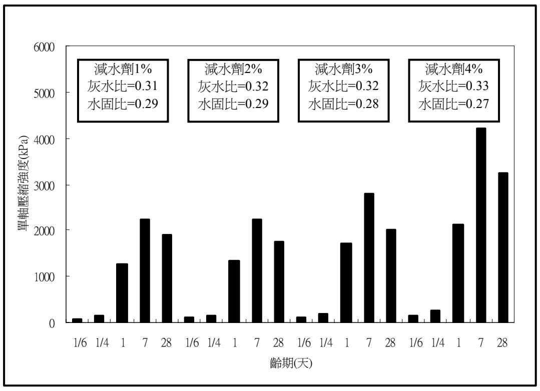

圖 6 減水劑與底渣流填料單軸壓縮強度之關係

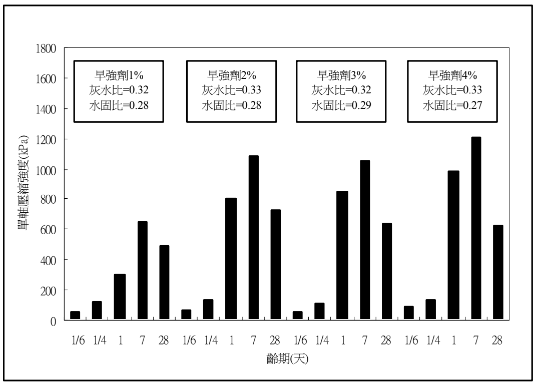

圖 7 早強劑與底渣流填料單軸壓縮強度之關係

# 附件

一、出席國際學術會議報告
二、發表學術論文

## 行政院國家科學委員會補助國內專家學者出席國際學術會議報告

94 年 9 月 20 日

| | | | |
|---|---|---|---|
| 報告人姓名 | 吳淵洵 | 服務機構及職稱 | 中華大學土木工程系副教授 |
| 時間<br>會議<br>地點 | 2005/8/21-2005/8/24<br>美國德州休斯頓市 | 本會核定補助文號 | NSC 94-2211-E-216-006 |
| 會議<br>名稱 | (中文)美國土木工程學會 2005 管線工程研討會<br>(英文) ASCE Pipeline Conference 2005 | | |
| 發表<br>論文<br>題目 | (中文) 土壤流填料於管線工程之應用<br>(英文) Soil-Based Flowable Fill for Pipeline Construction | | |

報告內容應包括下列各項：

一、參加會議經過

美國土木工程師學會(ASCE)管線工程組(Pipeline Division)為促進世界管線工程技術之發展，每年均會針對特定主題召開國際性研討會，廣邀世界各地專家、學者及業者與會交流討論。由於 ASCE 在國際土木工程界素負權威及其慎重規劃之態度，故每次研討會多吸引全美及世界各地產官學界菁英與會，蔚為風潮。今年該組以「現代經濟條件下，管線工程設計、營運與維護之最佳化」為主題，籌辦「2005 管線工程研討會」，針對近年來管線工程技術於世界各地眾多管線建設中之影響與發展，邀請與會者專案討論。報名參與會議人數達 206 人，參展相關廠商亦達 56 家。會議內容涵蓋管線工程技術於各類建設之應用包括自來水、廢水、各類油品，以及瓦斯之輸送等，相關領域包括無開挖管線技術、規劃與施工、研究與發展、現況評估、修復與監造、緊急修復、地震設計、油品及瓦斯、管線流量計算、管線內襯及外膜技術、暫態流及水力分析及模擬、管線基礎及回填、壓力管線監造技術等總計達 33 項議程。8/21 為訓練課程，正式會議則分別於 8/22~8/24 次第展開。會場設於休斯頓市之 InterContinental Hotel。

報告人於 8/20 自臺灣啟程赴美，於當地時間 8/21 下午抵達會場 InterContinental Hotel 報到，領取會議資料。8/22 會議正式展開，早上 8:00 至 10:00 首先由美國管線工程重量級的專家 Ken Kirk(National Association of Clean Water Agencies 總裁)進行開幕專題演講，介紹美國基礎建設(infrastructure)的近況。休斯頓市公共工程局局長 Michael Marcotte 說明都市老舊設施更新的迫切性與必要性。環保署飲水計畫主持人 Tom Poeton 報告美國計畫於未來五年內持續投資約 1.6 兆美元，用以修復、汰換老舊的基礎設施，其中包括各種民生管線如自來水、廢污水下水道管線，以及天然瓦斯、電氣、通訊、油料管線等。專題演講結束後隨即同步展開各場次之議程。報告人上午參加「無開挖管線技術」，下午則參加「老舊管線狀況評估及更新」

及「管線施工與監造」等場次。報告者分別來自美、加國各地。其中以無開挖管線公司總裁 Thomas Meinhart 提出關於「無挖管線技術應用於高壓管線之設計與施工」令報告人印象最為深刻。無開挖管線技術對於都市市容及道路品質之維護，以及交通安全之保障均具有極高之效益。高壓管線之施工要求與一般民生管線迥異，故其設計與施工均具有特殊考量。報告人以實務案件為例，說明無開挖管線技術應用於高壓管線之設計與施工之方法，所遭遇之困難與改善對策，以及注意事項等。無開挖管線技術在國內之研究方興未艾，其中多項創新工法聞所未聞，值得再進一步蒐集資料學習。

8/23 上午議程主題包括管線緊急修復、油料與瓦斯管線、流量分析與計算等。下午則為管線之滲漏及管線規劃與設計等。各場次均有多篇論文值得多所學習與探討。其中以 LAN 副總裁 Ortega 提出之管線破損緊急修復之創新工法最具價值。由於管線老舊以及使用人口增加，導致流量倍增，因而使得休斯頓市在過去五年來頻頻發生爆管事件，造成市民極度反感，質疑施工品質影響政府威信。Ortega 先生依據其整治及搶修經驗，以實例說明爆管避免對策以及緊急修復工法，其中以加壓滑動內模工法極具創新性。我國近年來亦頻傳管線破壞事件，本篇論文值得國內加以借鏡。

8/24 參加之場次為地震及水下管線之設計、壓力管線之施工技術，以及墊層、回填料之施工。由來自美、日、伊朗等地之專家與學者分別發表數篇有關地震及水下管線之工法與實務案例之經驗分享，其中由日本神戶大學研究員 Kuwata 報告之論文「斷層位移之計算、對管線之影響及其對策」與我國情形相似性最高。Kuwata 以差分元素法建立管線模型用以模擬分析計算斷層可能造成之管線位移。依據分析結果建立計算公式，並得以歸納可能產生之位移。依據計算結果設計管線之柔性接頭從而避免地震位移對管線造成可能之損害。我國管線甚多位於斷層地區，故此種分析技術頗值得參考。8/24 上午報告人出席「墊層及回填料」並發表論文：「土壤流填料於管線工程之應用」，說明此種以現地土石作為流填料之工法優缺點、配比設計實驗方式，以及大型現地試驗結果。本日雖為研討會的最後一日，出席者仍相當踴躍，且對於本人之論文提出相當多的詢問與討論，並多著重於實務應用方面。說明土木研究應理論與實務並重，僅專注於理論而疏於實務應用，則再好的研究也僅只於空談，不具應用價值。8/24 下午，大會安排的活動為現場工程參觀(technical tours)或參展區自由交流活動。由於飛機行程之限制，報告人僅能於參展區作最後的瀏覽。本次研討會參展廠商眾多，展示商品種類及內涵包括材料、設計、施工及電腦程式等均極為豐富。報告人如入寶山收獲甚多。在參展場次結束後隨即離開會場，結束此次美國 2005 管線工程研討會學習之旅。

## 二、與會心得

本次研討會參加者達 206 人，對於一個單一工程主題的會議，竟然可吸引如此眾多的與會者，其主要原因當係主辦單位素負權威、規劃週詳，且會議主題切合潮流，使得會議內容豐富精彩；其二則為產官學界之全力支持，由此可見得美國工程界對整合研究與實務方面之重視及用心。我國管線工程

界相關單位眾多，每年於研究方面亦分別投入不少人力與經費，但整合效果似乎不彰殊為可惜。ASCE 籌辨研討會之模式實值得國內管線相關單位之參考。

管線工程建設包含各種專業領域，土木工程僅為其中一部分，而報告人所屬之大地工程更僅為土木工程之一支，但因其與任何管線工程設施之基礎安全息息相關，故其重要性十分明顯，而此點亦在此次會議中眾多發表之論文得到印証。在所有場次中，不少論文相當精闢且意義重大，值得令人學習與深思。對個人而言，當以管線回填材料性質這一部分價值最為重要。經過本次研討會之研習，不但印証報告人過去數年來於國科會支持下，針對此一研究方向努力之正確性，符合世界潮流與趨勢，同時亦增加不少關於管線流量分析、生命週期與緊急修復對策之新知。感謝國科會與中華大學對於相關研究計畫及對於參加本次研討會經費之支持。

此次參加會議亦得以認識大會承辦人美國德州休斯頓大學 Vipulanandan 教授、San Diego 自來水公司資深工程司 Galleher、Lockwood 顧問公司 Henry 經理、URS 公司副總裁 Urlich 等 20 餘位世界各地的專家與學者並就研究所知與工程經驗交換心得。綜合言之，本次參加研討會研習收獲豐碩，鑑於 ASCE 舉辦之學術研討會價值與地位倍受世界各地之重視，報告人至盼未來仍有機會再度與會研習新知。

## 三、考察參觀活動(無是項活動者省略)

本次會議因行程限制未參加任何工程參觀活動。

## 四、建議

依據報告人之研習與參訪所得，建議：

1. 美國 ASCE 相關主題之研討會學術與實務價值極高，對整合理論與實務極具成效，落實研發成果與技術之推廣，國內工程界應引為借鏡。國科會歷年舉辦之研究成果發表會具有類似功能，惜工程界參與者不甚踴躍，建議比照 ASCE 模式廣邀實務界擴大辦理。
2. ASCE 相關主題之研討會吸引世界各地菁英與會，國人不應缺席，應儘量爭取國際地位，惜此次會議看到之國內同業僅一中興大學的博士生，建議國科會宜寬列預算，儘量鼓勵國內學者專家參加此種大型國際研討會。

## 五、攜回資料名稱及內容

美國 ASCE「20042005 管線工程研討會會議論文集」及大會各參展廠商提供之資料等。

*Pipeline 2005, Proceedings of the Pipeline Division Specialty Conference, ASCE, Houston, Texas, 2005, pp. 925-938*

# Soil-Based Flowable Fill for Pipeline Construction

Jason Y. Wu[1], D.Eng.Sc., P.E.

## Abstract

This research investigated the performance of a soil-based flowable fill as an alternative backfill for pipeline construction. The excavated natural silty sand from a trench was used as the major ingredient in the flowable fill. The study consisted of two phases. In phase I, laboratory experiments were conducted to develop optimum mix formula. Tests included physical properties, flowability, and strength. In phase II, field trial construction was conducted to verify the accuracy of laboratory results and evaluate the field performance of the material. Based on the research, for strength values ranging from 300 to 1,000 kPa, the cement-to-water and water-to-solid ratios were the two most important parameters controlling the engineering performance of the material. Laboratory and field observations provided strong evidence that the use of soil-based flowable fill can be a practical solution and promote optimum quality for pipeline construction.

## Introduction

The quality of the backfill around pipelines has great importance for pipeline safety (Kaneshiro, et al., 2001). It is important regarding bearing safety, settlement minimization, and service ability of the constructed facility. However, the compaction criteria in many instances are difficult to achieve because site restriction, soil conditions, equipment limitation, and workmanship. In addition, backfill sometimes even with controlled compaction still exhibits a collapse phenomenon or other adverse problems leading to difficult pipeline remedial works (Lawton et al. 1989).

---

[1] Associate Professor, Department of Civil Engineering, Chung Hua University,
707 Sec. 2, Wufu Road, Hsinchu, Taiwan 30012, ROC

*Pipeline 2005, Proceedings of the Pipeline Division Specialty Conference, ASCE, Houston, Texas, 2005, pp. 925-938*

Controlled low-strength material (CLSM) or flowable fill is a self-compacting, flowable, durable strength, cementitious material used primarily as backfill, void fill, and utility bedding in lieu of conventional compacted fill (Kaneshiro et al. 2001; Du et al. 2002). It consists of water, cement, fly ash or other similar by-products, and fine or coarse aggregates or both (Hitch 1998; ACI 1994). Its performance and criteria for pipeline construction are well documented in the literature (Webb et al. 1998; Hook and Clem 1998; Kaneshiro et al. 2001). In comparison with conventional granular backfill, it exhibits many advantages such as easy construction, low cost, high strength, and low compressibility. In many cases, it facilitates the backfill operation and ensures the construction quality (Kaneshiro et al. 2001; Samadi and Herbert 2003). However, there are also several disadvantages to the use of flowable fill such as industry unfamiliarity, unclear specifications, possible corrosivity, potential material variability, long-term removability, deeper frost penetration, and a delayed setting time (Baker 1998; Kaneshiro et al. 2001; Samadi and Herbert 2003).

Another problem associates with conventional flowable fill is that the use of specified aggregate has imposed natural resource deficiencies and ecological problems in many areas. In many cases, it is also difficult to find a proper place to disposal of the excavated soil for the pipelines (Kaneshiro et al. 2001; Du et al. 2002). Developing a better solution for pipeline backfill appears to be necessary to optimize the pipeline construction.

This paper presents the results of an experimental study and field observation using a soil-based flowable fill as an alternative for the conventional granular backfill used in pipeline construction. Laboratory experiments developing a suitable mix design are first described, followed by performance observations during field installation.

The native silty sand excavated from the trench for a conduit bank was mixed with cement and water to produce a modified version of conventional flowable fill. Use of such material tended to: (1) ensure backfill quality; (2) lower construction cost; (3) reduce consumption of natural quarry resource; and (4) promote resource recovery for spoil soil and ecological benefit.

## Experimental Program

The purpose of this study was to develop a practical scheme for pipeline construction using a soil-based flowable fill with local site material. The ideal properties of the material would be flowable, strong, and durable. Based on other studies, flowability and strength are the two most important properties for flowable fill (ACI 1994; Hitch 1998; Du et al. 2002). Therefore, the weight ratio of cement-to-water (C/W) and water-to-solid (W/S) were selected as control parameters for the mix design.

To verify the engineering properties in detail, the experimental program consisted of two series of laboratory studies. Series I conducted an initial evaluation of the proper design mixes for flowable fill. Tests included physical properties, flowability, and strength. An optimum design mix formula corresponding to the most appropriate flowability and strength were selected for the series II study. Representative samples were then examined for permeability, compressibility, hydrocollapse, bearing capacity, and undrained shear strength based on the aspects of geotechnical engineering. All tests were performed in accordance with the procedures and corresponding standards outlined in the ASTM. The laboratory mixtures were then used as the basis for the field trial installation.

The materials used in this study consisted of silty sand, cement, and water. The sand was taken at the proposed construction site. It was a yellowish brown fine sand with some non-plastic silt. It was classified as SM for USCS system or A-2-4 for AASHTO system. For regular samples, portland type I cement was used. For early-strength studies, a special calcium aluminate cement (CAC) was used. All samples were first blended in dry following the prescribed mix formula. Water was then introduced and sample was mixed and tested accordingly.

## Test Results and Discussion

***Flowability.*** Flowability is the most promising feature for flowable fill in superior to a conventional backfill. In general, flowability is controlled by the amount of water contained in the composite. The larger amount of water it uses, the higher the flowability it has. However, a greater water content may cause aggregate segregation, bleeding increase, and strength reduction. Therefore, the selection of a suitable water content making the material exhibit the best engineering performance was the first priority for the mix design.

Procedures recommended by the ASTM D-6103 were used to measure flowability. Measurements were conducted by filling a 75 mmϕ×150 mmH open-end plastic cylinder with flowable fill on a leveled non-absorptive surface and then raising the cylinder quickly allowing the slurry to spread freely on the surface. When the slurry stopped flowing, the diameter of the slurry was measured in two orthogonal directions. The average diameter was recorded and defined as flowability for that composite. For most applications, specification requires a typical diameter to be 200 mm or greater with no visible segregation (Crouch et al. 1998).

*Pipeline 2005, Proceedings of the Pipeline Division Specialty Conference, ASCE, Houston, Texas, 2005, pp. 925-938*

Figure 1 presents the effect of the C/W and W/S ratios on the flowability of each sample tested. The results indicated that flowability increased with the increase of the W/S ratio but the rate of increase became insignificant when the W/S ratios were greater than 0.5. Increasing the amount of water tended to reduce the shear resistance within the soil particles. Therefore, the flowability was increased. When the shear resistance dropped to the minimum, further increasing the amount of water showed only a minor effect on the flowability. A W/S ratio of 0.6 appeared to be the threshold value for the maximum flowability.

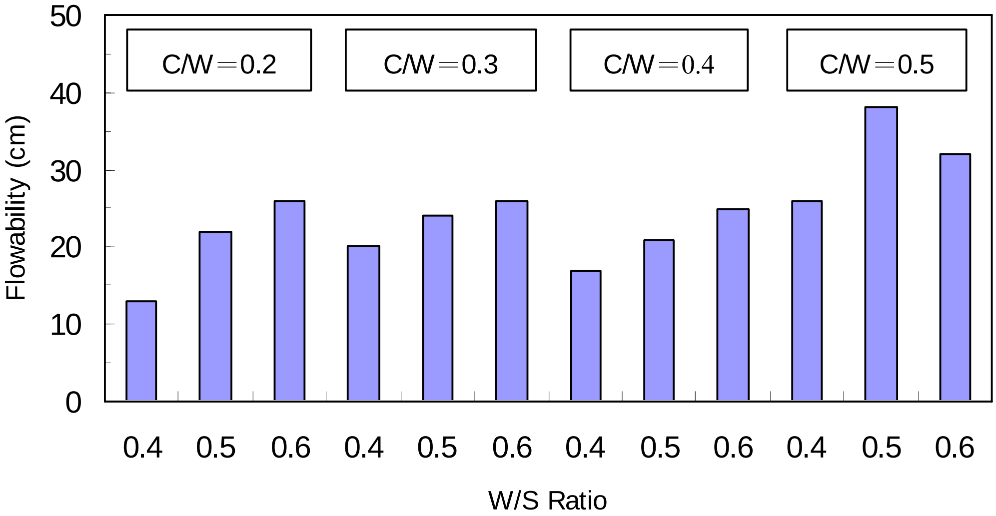

**Figure 1**. Comparison of flowability for samples with different compositions.

The change of flowability with the C/W ratio was insignificant. This is because the amount of solid was fixed for a specified mix proportion. Increasing the amount of cement would cause the soil used to be reduced an equal amount. Based on the above discussion, the W/S ratio is the predominant parameter that controls flowability. Laboratory observations indicated that a flowability of 150 to 300 mm would satisfy the requirements of flowability and self-leveling. Therefore, W/S ratios of 0.4 to 0.6 can be used as a criterion for flowability design.

***Strength.*** The flowable fill gradually hardened and achieved strength through the hydration of the cement. The composites were examined for strength after curing them for 1, 7, and 28 days. Figure 2 and Figure 3 present the effects of all parameters on the unconfined compression strength ($q_u$) for samples cured with 1-day and 28-day. The values of $q_u$ increased with the increase of the cement content and curing time. However, higher W/S ratios tended to reduce $q_u$. The values of $q_u$ cured for one day ranged from 52 to 773 kPa and those for a 28-day curing period were 312 to 6,549 kPa. The tendency to increase was more significant for samples with higher C/W ratios and curing time. Such phenomenon can be attributed to the continuing cementation reactions. The C/W ratio can be considered as an effective control parameter for strength.

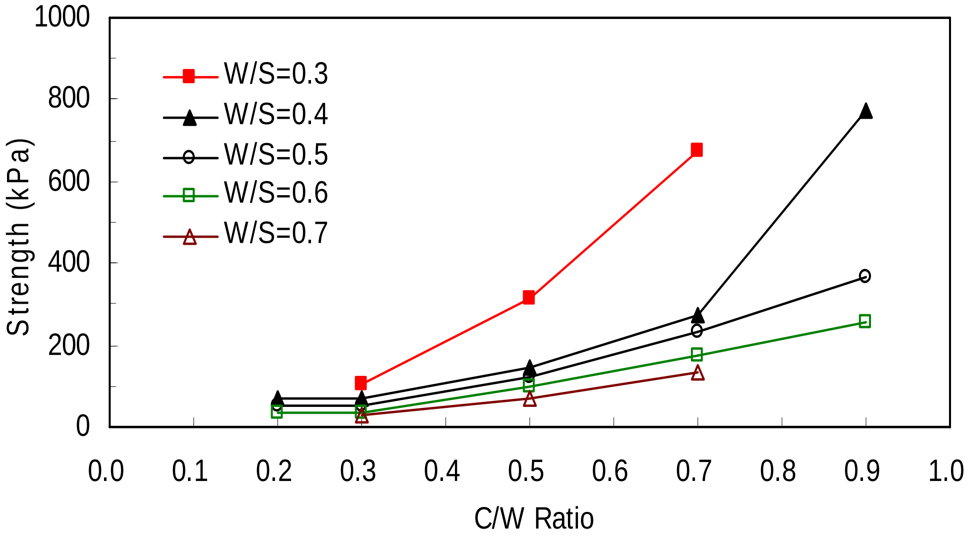

**Figure 2**. Typical variations of strength with C/W and W/S for 1-day samples.

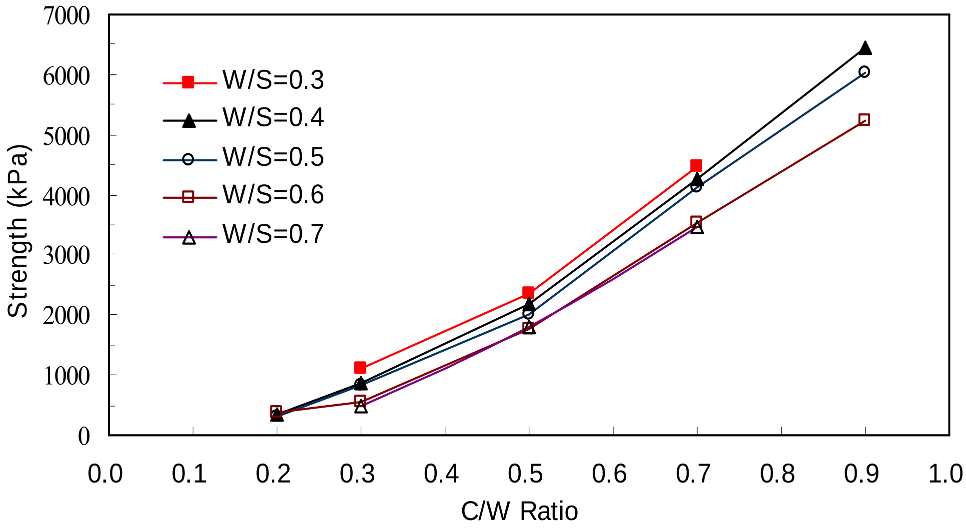

**Figure 3**. Typical variations of strength with C/W and W/S for 28-day samples.

The typical strengths recommended and required for pipeline installations would be 340 to 690 kPa (Kaneshiro 2001). The ultimate strength for an excavatable CLSM is about 1,000 kPa (Crouch et al.1998). In general, the observed 28-day strength for any sample tested had more than enough strength to meet such a requirement. Higher strength can be achieved with higher cement content. However, the possibility of future backfill removal must be considered. Based on the above findings, the recommended C/W and W/S ratios for a suitable flowable fill should be 0.3 to 0.5 and 0.4 to 0.6, respectively

*Pipeline 2005, Proceedings of the Pipeline Division Specialty Conference, ASCE, Houston, Texas, 2005, pp. 925-938*

***Early Strength.*** For some projects, the backfill is required to be completed immediately after the installation of the pipeline. Construction in areas with heavy traffic is a typical example. For such conditions, flowable fill will not be applicable unless it hardens and gains reasonable strength within a limited time. Considering the requirement of traffic loading and the available practices of flowable fill, the design early strength was set for 200 kPa within 2 to 4 hours.

For flowable fill, high early strength is difficult to achieve because it is in conflict with the requirement of flowability. Previous studies with various amounts of accelerators such as calcium chloride and sodium silicate were conducted. However, they did not improve the set time and the early strength as they do for concrete. For an acceptable strength, set time cannot be reduced within 2 hours. The unsuccessful results can be attributed to the fact of the higher water content and lower cement used in the composite (Wu 1999).

In this study, calcium aluminate cement (CAC) was used to observe its effect on the set time and the early strength. Compared to portland cement, CAC possesses higher early strength and superior durability to sulfate attack (Mehta and Monteiro 1993). The principal compound in CAC is monocalcium aluminate (CA). Although CAC products have setting times comparable to ordinary cement, the rate of strength gain at early ages is quite high mainly due to the high reactivity of CA. Within 24 hours of hydration, the strength of normally cured CAC concretes can achieve values equal to or exceeding the 7-day strength of ordinary cement (Mehta and Monteiro 1993).

Tests with CAC were conducted with procedures similar to those with ordinary cement. Representative test results for a W/S ratio of 0.3 are presented in Figures 4. It can be seen that samples with C/W ratios of 0.3 to 0.4 were able to meet the design strength within 2 to 4 hours. However, after 7 days of curing, it was also found that their long-term strength decreased with time. This tendency was not stable until 42 days (1,008 hours). The reductions were up to about 70% in comparison with those of the 28-day samples.

The changes were mainly because the principal hydration product ($CAH_{10}$) was thermodynamically unstable, especially in warm and humid storage conditions. It gradually transformed into a more stable compound ($C_3AH_6$) with a denser structure. The $CAH_{10}$–to-$C_3AH_6$ conversion was associated with a large increase in porosity and therefore a corresponding decrease in strength (Mehta and Monteiro 1993).

The final strengths of the CAC mixtures ranged from 240 to 430 kPa. To conform to the criteria of flowable fill as a backfill, the C/W ratio should be at least 0.4 based on the laboratory observations made to date. Further studies are underway to observe the long-term behavior of soil-based flowable with CAC.

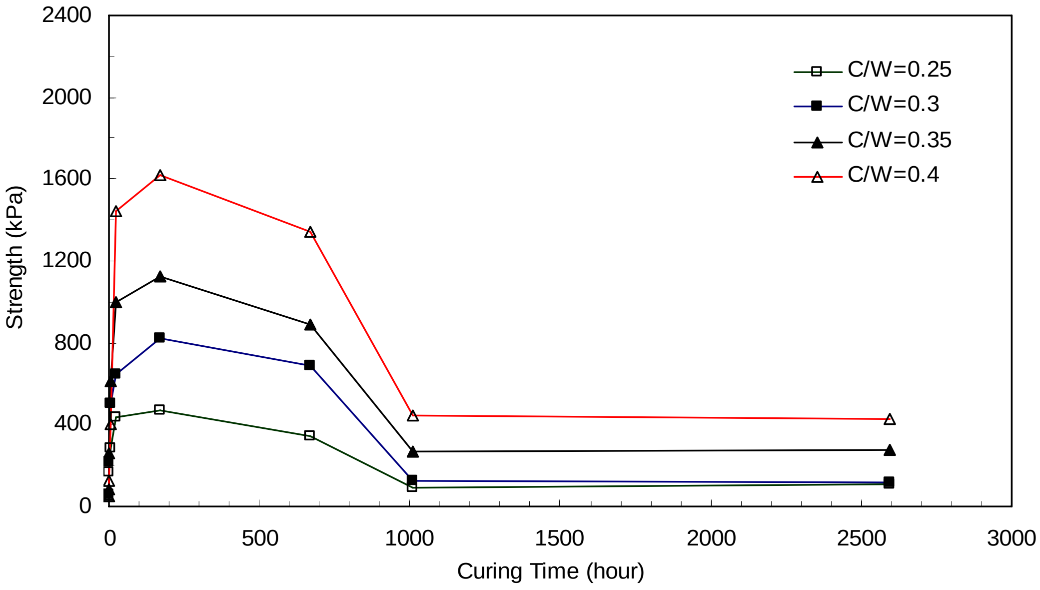

**Figure 4**. Typical variations of CAC early strength with C/W and curing time (W/S = 0.3).

## Geotechnical Properties

The proposed soil-based flowable fill was designed for pipeline backfill. Therefore, its suitability was verified following aspects of geotechnical engineering. Based on the above studies, a representative mix formula (C/W = 0.4, W/S = 0.5) was selected to prepare samples for further tests on permeability, compressibility, hydrocollapse, and bearing capacity. Because of the limitation of the project schedule, the curing time for most of the samples was restrained to one day.

***Permeability.*** The permeability of the representative sample was tested by using the falling-head technique. Test results were on the order of $10^{-7}$cm/sec, which is comparable to a clayey material. Backfill with such an impervious nature would be favored for pipeline construction designed against the attack of groundwater and frost penetration. However, for pipelines that require a pervious backfill, exceptional ingredients such as air-entraining agents must be used to improve the permeability.

***Compressibility.*** The compressibility of cementitious material usually is minimal due to the effect of cementation. To verify such an effect on flowable fill, one-dimensional consolidation tests were conducted. As shown in Figure 5, settlement increased with the increase of loadings for all samples tested. The virgin compression ratios ranged from 0.07 to 0.13 and the recompression ratio was 0.004. The preconsolidation pressure ranged from 1,500 to 1,800 kPa. It appears that the solidified flowable fill was heavily overconsolidated by the cementation. The changes of settlement appeared to have minor scatter with the curing time. This is probably due to different development of cementation with time for the sample structures. However, in general the compressibility observed for all samples tested were minimal. For such soil conditions, detrimental settlement is unlikely to occur with commonly imposed traffic loads on pipelines.

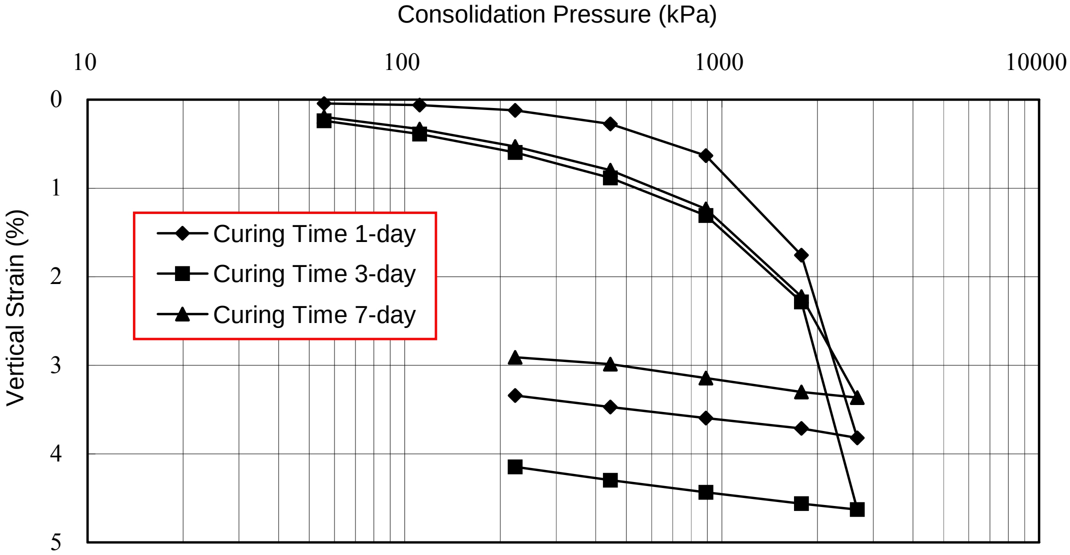

**Figure 5**. The consolidation behavior of the representative flowable fill (C/W=0.4, W/S=0.5)

***Hydrocollapse***. Compacted fills are often influenced by post-construction wetting due to rainfall or groundwater effect (Lawton et al. 1989). Therefore, the potential of hydrocollapse ($I_c$) for the fill material must be examined. The test was conducted according to the procedures outlined in the ASTM D-5333 and the results are presented in Figure 6. The observed hydrocollapse of the sample was 0.029% under a loading of 450 kPa. Based on Jennings and Knight (1975), fill materials with $I_c$ over 1% will be vulnerable to hydrocollapse damage. Therefore, the solidified flowable fill will probably not have hydrocollapse problems.

For comparison, a similar test was conducted using the same sandy soil prepared for the flowable fill testing. The sample was compacted to 95% modified Proctor density and with moisture content 4% less than the optimum. The observed $I_c$ was 1.04%, which showed about a 34-fold increase over the value of flowable fill. The effect of cementation on the flowable fill drove out the occurrence of hydrocollapse.

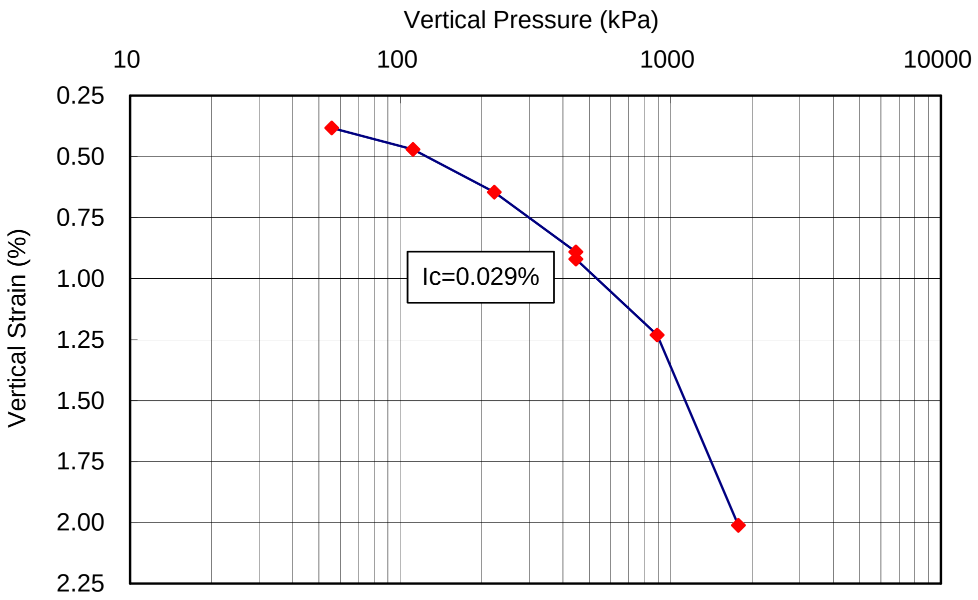

**Figure 6**. The potential of hydrocollapse of the representative flowable fill (C/W=0.4, W/S=0.5)

***Bearing Capacity.*** The bearing capacity of the flowable fill was evaluated by its California bearing ratio (CBR). The reported value was 77, which was equivalent to that of a well-graded gravel material (Carter and Bentley 1991). Therefore, flowable fill developed in this study is competent for pavement support.

***Shear Strength.*** A triaxial shear strength test was conducted to examine the undrained shear strength of the proposed flowable fill. It was found that the deviator stress at failure increased with the increase of confining stress. The observed cohesion (c) was 103 kPa and the angle of shearing resistance ($\phi$) was 16.7°. This is equivalent to a value of undrained shear strength of about 120 kPa for a depth of backfill 2 to 3m. The undrained shear strength was not high as the sample was cured for only one day. The strength was predominantly supported by the cohesion developing due to the cementation of the cement. Interlocking in the particles was weak because of the greater amount of water within the soil pores at that time. Further studies on shear strength for longer curing time are underway.

## Field Observation

***Batch Mix Design.*** Based on the laboratory test results, the optimum mix design for regular soil-based flowable fill would be 0.3~0.5 for the C/W ratio and 0.4~0.6 for the W/S ratio. The observed 28-day strength ranged from 650 to 2,250 kPa. The average unit weight of the mixture was about 17.0 kN/m$^3$. Table 1 presents the batch mix proportions (per cubic meter) based on the laboratory findings for field application. Considering the traffic conditions at the test site, the final mix design for the trial construction was 0.3 for C/W and 0.4 for W/S. Early-strength flowable fill was not conducted in this trial due to its uncertainty.

**Table 1** Mix proportions for field application

| Material | Quantity (kg/m$^3$) |
|---|---|
| cement | 159~314 |
| soil | 1165~629 |
| water | 529~733 |

The project selected for the field observation was a telecommunication conduit bank placed along the sidewalk of a major arterial street. There were four layers of conduits in the bank and supported in line by a concrete rack. Their proximity to each other caused compaction to be virtually impossible (Figure 7). Use of a flowable fill with its behavior of self-leveling and self-compacting made the placement for this type of construction fast and easy.

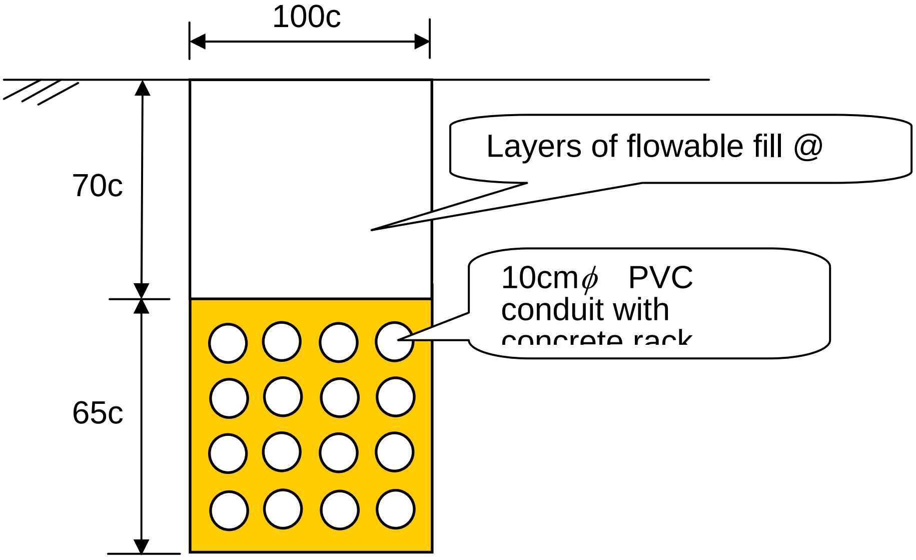

**Figure 7**. Typical trench cross section for trial construction

***Trial Construction.*** The preparation of the flowable fill in this field trial was conducted by a Komatsu PC 200 backhoe only (Figure 8). The batched quantity of soil and water was measured based on the volume of the backhoe bucket. The purpose of that was to simulate situations where standard batching facility is not available or is not affordable. Such conditions are likely present during the construction of many pipeline projects. For example, when the ready-mix truck is not accessible due to site constraints, the backfill quantity is small, the shipping distance is long, or the night-time delivery charge is too costly etc.

The excavated soil from the trench was placed in a steel batch bin of 8 m$^3$ in volume. Bags of cement were then loaded in and thoroughly mixed using a backhoe. Water was then filled to the predetermined volume by a water truck. The fill-in volume of the mixture was limited to 5 m$^3$ to allow sufficient space for the backhoe operation. Mixing was continuous until the tested flowability values met the specified requirement. The flowability of each batch was examined on site using an open-end-cylinder flow test as per ASTM D-6103. The qualified mixed materials were then delivered to the trench by backhoe. The turn-around time per batch was 18 to 22 minutes. The operation was continuous, and a trial section of 30 m for such placement were completed in less than three hours.

**Figure 8**. Soil-based flowable fill mixed with a backhoe

***Field Assessment.*** Test cylinders were prepared during the backfill installation. After curing at the site for one day, the cylinders were placed in moistened sand boxes and sent to the laboratory for further curing and testing. Upon placement of the mixtures, surface bearing capacity values of the flowable fill in the trench were examined using a Clegg Impact Tester following procedures specified in the ASTM D-5874 (Figure 9). The measurement involved a free fall of a digital hammer on the surface. The impact value (IV) was shown on the hammer's direct reading and can be correlated to the bearing capacity values by calibrations. In conjunction with the bearing capacity observations, the variations of settlement with time of the mixtures were monitored from a benchmark established near the trench. All field measurements were performed at 1 day, 7 days and 28 days from the placement of the flowable fills. The results of field measurements are summarized in Table 2.

It can be seen that the flowable fill appears to be soft for the initial 24 hours, however, its strength increased with time. The tendency to increase is similar to those found in the laboratory. The average 28-day strength observed for these cylinders was 540 kPa, which was comparable with those found in the laboratory. The equivalent bearing capacity ratio based on impact values was about 41, which will be more than enough as pavement subgrade. The settlement values also increased with time, however, they all can be considered insignificant. Based on the field trial, the use of soil-based flowable fill as an alternative backfill can be a practical solution for pipeline construction.

**Figure 9**. Examine the bearing capacity with Clegg Impact Tester

**Table 2** Summary of field measurements

| Test I.D. | Unit Weight (kN/m$^3$) | Flow'ty (mm) | Unconfined Comp.Strength (kPa) | | | Impact Value | | | Accumulated Settlement (mm) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 day | 7 days | 28 days | 1 day | 7 days | 28 days | 1 day | 7 days | 28 days |
| *1 | 19.2 | 188 | 144 | 488 | 520 | - | - | - | - | - | - |
| *2 | 17.6 | 170 | 160 | 500 | 560 | - | - | - | - | - | - |
| #1 | - | - | - | - | - | ! | 15 | 17 | 1.5 | 2 | 11 |
| #2 | - | - | - | - | - | ! | 22 | 25 | 1.2 | 3 | 10 |
| #3 | - | - | - | - | - | ! | 18 | 20 | 1.0 | 1.0 | 7 |
| #4 | - | - | - | - | - | ! | 17 | 21 | 1.0 | 1.0 | 12 |

[*] Cylinder sample collected per batch.

[#] Monitor location on the trench surface.

[!] Unable detect resistance.

## Conclusions

The results of this study provide the following conclusions:

- The increase of the W/S ratio caused an increase in flowability. It also caused a decrease in strength. The increase of cement-to-water ratio caused the strength to increase significantly but it did not show definite relationship with flowability.
- The strength increased with curing time. This tendency is attributed to the continuing cementation reactions. Such effect is more prominent for higher cement content.
- The strength that required for common pipeline backfill ranges from 340 to 1,000 kPa. Considering such requirement as well as other engineering criteria, soil-based flowable fill with cement-to-water ratios of 0.3 to 0.5 and water-to-solid ratios of 0.4 to 0.6 are recommended.
- Use of calcium aluminate cement (CAC) for the preparation of flowable fill showed an increase in early strength for the initial 7 days. It then decreased with time and finally became stable after about 42 days. Despite the decrease, the final strength meets the criteria for backfill. Further studies are necessary to observe the long-term behavior of flowable fill materials with CAC.
- Geotechnical test results proved that the proposed flowable fill appears to have sound engineering properties based on geotechnical aspects.
- The trial construction demonstrated that batch mixing of a soil-based flowable fill with a backhoe in the field is practical. The placement can be completed within a reasonable time and makes it attractive from the standpoint of cost reduction.
- Field measurements of all engineering properties are similar to those found in the laboratory. The results of field observations provide strong evidences that the use of a soil-based flowable fill can be a practical solution for pipeline construction.

## Acknowledgements

This project was partially funded by the National Science Council, ROC, Project No. NSC 92-2211-E-216-005. Their support is greatly appreciated.

## References

American Concrete Institute (1994). “Committee 229, ACI 229R-94 report: controlled low strength materials (CLSM).” *Concrete International,* 16(7), 55-64.

Baker, T. H. W. (1998). “Frost penetration in flowable fill used in pipe trench backfill.” *The Design and Application of Controlled Low-Strength Materials (Flowable Fill),* ASTM STP 1331, 275-282.

Carter, M., and Bentley, S. P. (1991). *Correlations of soil properties,* Pentech Press Limited, London.

Crouch, L. K., and Gamble, R., Brogdon, J. F., and Tucker, J. (1998). "Use of high-fines limestone screenings as aggregate for controlled low-strength material (CLSM)." *The Design and Application of Controlled Low-Strength Materials (Flowable Fill),* ASTM STP 1331, 45-59.

Du, L., Folliard, K. J., and Trejo, D. (2002). "Effects of constituent materials and quantities on water demand and compressive strength of controlled low-strength material." *J. Materials in Civil Engineering*, ASCE, 14(6), 485-495.

Hitch, J. L. (1998). "Test methods for controlled low-strength material (CLSM): past, present, and future." *The Design and Application of Controlled Low-Strength Materials (Flowable Fill),* ASTM STP 1331, 3-10.

Hook, W., and Clem, D. A. (1998). "Innovative uses of controlled low strength material (CLSM) in Colorado." *The Design and Application of Controlled Low-Strength Materials (Flowable Fill),* ASTM STP 1331, 137-150.

Jennings, J. E. and Knight, K. (1975). "A guide to construction on or with materials exhibiting additional settlement due to collapse of grained structure." *Proceedings, 6th Regional Conference for Africa on Soil Mechanics and Foundation Engineering,* South Africa, 1, 99-105.

Kaneshiro, J., Navin, S., Wendel, L., and Snowden, H. (2001). "Controlled low strength material for pipeline backfill – specifications, case histories and lessons learned." *Proceedings, Pipeline 2001*, San Diego, California,1-13.

Lawton, E. C., Fragaszy, R. J., and Hardcatle, J. H. (1989). "Collapse of compacted clayey sand." *J. Geotechnical Engineering,* ASCE, 115(9), 1252-1267.

Mehta, P. K. and Monteiro, P. J. M. (1993). *Concrete structure, properties, and materials.* Prentice-Hall, Inc., New Jersey.

Samadi, A., and Herbert, R. (2003). "Corrosiveness of controlled low strength materials vs. that of encasement sand." *Proceedings, International Conference on Pipeline Engineering and Construction 2003*, Baltimore, Maryland, 514-523.

Webb, M. C., McGrath, T. J., and Selig, E. T. (1998). "Field test of buried pipe with CLSM bsckfill." *The Design and Application of Controlled Low-Strength Materials (Flowable Fill),* ASTM STP 1331, 237-254.

Wu, J. Y. (1999). *The application of flowable fill for backfill construction (in Chinese).* Report No. NSC 88-2218-E-216-005, National Science Council, R.O.C.