Evaluation of controlled low strength materials containing red brick construction waste based on mechanical experiments and BP neural network

J G Wang1,2 and J X Zhang1*

1 Beijing Key Laboratory of Transportation Engineering, Beijing University of Technology, Beijing 100124, China
2 Solid waste R & D Center, Beijing Urban Green Source Environmental Protection Technology Co., Ltd, Beijing 102601, China
*Corresponding author: zhangjinxi@bjut.edu.cn

Abstract. In this study, two kinds of controlled low-strength materials (common and rapid-hardening) were designed and prepared by using red brick construction waste fines. Fourteen mixture specimens were prepared with the control parameters of binder to construction waste fine aggregate ratio (α), accelerator to binder ratio (β), and water to solid ratio (γ). The flowability of fresh mixtures, compressive strength of hardened materials were studied. Test results show that it is applicable to use the red brick construction waste fine aggregate to prepare controlled low-strength materials. Increasing α and γ can increase the flowability, however with different the influence mechanisms, where γ has a more significant effect. The 2 hour-strength of rapid-hardening CLSM (controlled low strength material) based on sprayed concrete accelerator can be up to 0.41~0.79MPa, which meet the needs of emergency backfill engineering. Using on the BP neural network, the long-term strength prediction model of CLSM is established, which can help the civil engineers in the material mix-design.

1. Introduction
The construction of large-scale new buildings and the demolition of abandoned buildings have consumed a large amount of natural stone and generated huge construction waste. It is estimated that by 2020, the amount of construction waste in China will reach 30 billion m³ [1]. Over-exploitation of sand and gravel materials will cause serious damage to cultivated land and vegetation, also the gravel material is a kind of non-renewable natural resources. To solve such problems, the treatment of construction wastes become necessary and urgent. In the recycled aggregates, better-quality recycled coarse aggregate (greater than 5 mm in diameter) has been used for the production of recycled cement concrete [2, 3], recycled blocks [4], etc., but the using of recycled fine material (particle size less than 5mm) with a large amount of red bricks, mortar, and dregs, etc. for recycling is very limited.

According to American Concrete Institute (ACI) Committee 229 [5], controlled low strength material (CLSM) is a self-compacting, self-leveling cement-based material that can replace the traditional backfill materials. CLSM typically consists of cement, fly ash, fines, etc., in which the cement can be partly replaced by by-products (as cementitious materials) such as slag [6], stainless steel slag [7], etc. Fly ash is a mineral admixture to improve workability, and enhance strength. With the largest amount of fine aggregates and higher freedom of material selection, it can make full use of local rich waste, such as surplus clay [8], solid wastes from paper mills [9], waste water treatment sludge [6], etc. In addition, it is convenient for pouring, without vibration or compaction, reducing the use of labor and construction
equipment, etc., where these advantages make it widely used in pavement base, bridge abutments fill and trench backfill [5, 9].

In addition, to reduce the disturbance of construction on the daily life of urban residents, it is necessary to carry out rapid construction. To meet the needs of different backfilling projects for hardening time and early strength, two types of CLSM (common and rapid-hardening) specimens are prepared using red brick construction waste fines, in which the early strength properties of rapid-hardening type are realized on the basis of spray concrete accelerator. Through testing the flowability of fresh CLSM and the compressive strength of hardened materials, the engineering properties are investigated and the feasibility of application to different backfill projects is discussed.

2. Experiments

2.1. Material design

The construction waste fine aggregate comes from a construction waste recycling plant in Shijingshan District, Beijing. Its distinctive feature is rich in red brick components. The screening results of the construction waste are shown in figure 1, in which the upper and lower limits of the screening curve are the grading ranges of the concrete fine materials specified in ASTM C33/C33M-13 [10]. The fine powder content (particle size less than 0.075mm) in construction waste fine aggregate is higher (12.2%), so it is not suitable to prepare recycled concrete, but it is very suitable for improving the cohesiveness and water retention of CLSM [11].

![Figure 1. Sieving curve of construction waste fine aggregate](image)

Radioactive substances exist widely in various building materials. Excessive irradiation may cause certain damage to human health [12]. In accordance with GB 6566-2010 [13], the safety inspection of building waste fine materials is executed, and the results are shown in Table 1. From Table 1, it can be seen that the radioactive indexes of construction waste fines meet the specifications, which is mainly due to the sources of construction waste, such as ordinary buildings, transportation infrastructure, etc. These construction waste does not contain special waste like those in the nuclear reactor protection facilities, indicating that the radiation effects of CLSM prepared by construction wastes in this study are safe to the human body.

Water may leach out of construction waste. Leaching harmful substances (hazardous heavy metals and anions, etc.) will migrate and transform, contaminate soil and groundwater, indirectly pollute crops, and threaten the human health. Therefore, according to GB 5085.3-2007 [14], the leaching toxicity detection of construction waste fines was carried out with an inductively coupled plasma atomic emission spectrometer. From table 1, it can be seen that the content of harmful components such as heavy metals in construction waste fines satisfies with the requirements of the standard. Construction waste will not cause secondary pollution to the environment when it is used in backfill projects as the component of CLSM.
Table 1. Detection results of radioactivity and leaching toxicity of construction waste fine materials

| Testing items                  | Test results | Standard requirements [13, 14] |
|--------------------------------|--------------|--------------------------------|
| **Radioactivity index**        |              |                                |
| Internal exposure index        | 0.2          | ≤1.0                           |
| External exposure index        | 0.4          | ≤1.0                           |
| Cuprum, Cu                    | <0.0001      | ≤100                           |
| Zinc, Zn                      | 0.023        | ≤100                           |
| **Concentration limit of**     |              |                                |
| **hazardous components in**    |              |                                |
| **leachate (mg/L)**            |              |                                |
| Cadmium, Cd                   | <0.0001      | ≤1                             |
| Arsenic, As                   | <0.0001      | ≤5                             |
| Hydrargyrum, Hg               | <0.0001      | ≤0.1                           |
| Plumbum, Pb                   | <0.0001      | ≤5                             |
| Nickel, Ni                    | 0.0004       | ≤5                             |
| Chromium, Cr                  | <0.0001      | ≤15                            |

In this study, the cement used is 42.5R ordinary Portland cement, the initial setting and final setting time are 140min and 180min respectively, and the 3-day and 28-day strength are 29.2MPa and 53.8MPa respectively. The Class F fly ash with fineness of 35%, water requirement ratio of 110%, is applied in this study. The accelerator used is a spray concrete accelerator produced by a building material company in China. This material is a dry powder formed by grinding a special sulphoaluminate clinker as a base material, which is commonly used in shotcrete. The mixing water uses common tap water.

2.2. Mix proportions, specimen preparation and testing procedures

2.2.1. Mix proportions

Table 2. Mix proportions and fresh properties of CLSM

| Type                | Binder to CWFA ratio (α) | Accelerator to binder ratio (β) | Water to solid ratio (γ) | Mix proportion (kg/m³) | Flowability (mm) |
|---------------------|--------------------------|---------------------------------|--------------------------|------------------------|------------------|
|                     | C   | A   | F   | CWFA | W   |                  |
| **Common**          |     |     |     |      |     |                  |
| 0.07                | 85  | 0   | 182 | 1210 | 413 | 190              |
| 0.10                | 118 | 0   | 177 | 1180 | 413 | 205              |
| 0.13                | 150 | 0   | 173 | 1155 | 414 | 213              |
| 0.15                | 170 | 0   | 170 | 1135 | 413 | 215              |
| 0.07                | 102 | 170 | 1135| 413  | 220 |                  |
| 0.10                | 102 | 170 | 1135| 414  | 220 |                  |
| 0.13                | 102 | 170 | 1135| 414  | 220 |                  |
| 0.15                | 102 | 170 | 1135| 414  | 220 |                  |
| **Rapid-hardening** |     |     |     |      |     |                  |
| 0.13                | 105 | 45  | 173 | 1155 | 414 | 209              |
| 0.13                | 75  | 75  | 173 | 1155 | 414 | 210              |
| 0.13                | 90  | 60  | 173 | 1155 | 399 | 192              |
| 0.13                | 90  | 60  | 173 | 1155 | 429 | 229              |
| 0.13                | 90  | 60  | 173 | 1155 | 444 | 263              |

Note: C = Cement, A = Accelerator, F = Fly ash, CWFA = Construction waste fine aggregate, W = Water, \(α = (m_C + m_A)/m_{CWFA} \), \(β = m_A/(m_C + m_A) \), \(γ = m_W/(m_C + m_A + m_F + m_{CWFA}) \).
To meet different engineering application requirements, two types of CLSM (common and rapid-hardening) were prepared, in which the rapid-hardening CLSM added sprayed concrete accelerator to realize the early strength. According to the mixing ratio design method in literature [11], 14 mixture specimens were designed and prepared based on the control parameters of binder to CWFA ratio ($\alpha$), accelerator to binder ratio ($\beta$), and water to solid ratio ($\gamma$), as shown in table 2. Fly ash can significantly improve the workability of fresh samples, and its amount should be 15% of the amount of construction waste fines [11]. By adjusting the amount of construction waste fines, the total volume of material per unit volume was controlled at 1860-1940 kg/m$^3$, where this range meet 1840-2230 kg/m$^3$ for normal CLSM [5].

2.2.2. Specimen preparation and testing procedures
The mixing of CLSM used a mortar mixer. According to the designed mix ratio, the weighed cement, accelerator, fly ash and dried-construction waste fines were added to the mixing pot, and then stirred thoroughly to the homogeneity. Finally, the mixing water was added and then stirred for 120 seconds. The flowability is one of the indispensable control indicators for CLSM engineering applications. Therefore, the flowability of the fresh mixture was tested with reference to ASTM D6103 [15] before pouring into the test mould. The test cylinder size was $\phi$75mm×150mm.

Compressive strength is a typical mechanical indicator for evaluating the bearing capacity of hardened CLSM. According to ASTM D4832 [16], a MQS-2 road material performance tester was used with a loading rate of 1 mm/min. The size of cylinder specimen was $\phi$100mm×200mm. Except for test specimens with early hour strength, other specimens were demoulded after 24 hours of pouring, and immediately moved into a humidity room until test. All test results were obtained by three parallel specimens.

3. Results and Discussion

3.1. Flowability
Flowability is a distinctive feature of CLSM that distinguishes it from traditional backfill materials. The good flowability enables it to be self-compacting without vibration in the pouring process. To ensure that the CLSM can maintain good workability, the minimum acceptable flowability in most applications is 180mm [8, 18]. As can be seen from Table 3, the flowability at different ratios was between 190mm and 263mm, which met the needs of general engineering. The flowability increased significantly with the increase of $\gamma$, and its growth tendency was significantly greater than the effect of $\alpha$ on flowability, which is similar to the results in the literature [8, 11]. The reason is that the increase of $\gamma$ leads to the increase of the free water content in fresh samples, which causes the particles to be in a “suspended” state, and reduces the friction between the construction waste fines and the cohesion between the gelled particles. According to ACI 229R [5], flowability greater than 200mm is a high flowability and can meet the needs of backfill projects such as a narrow operating space or dead corners. Therefore, for projects with high filling performance requirements, $\gamma$ should not be less than 0.28.

3.2. Compressive strength

3.2.1. Early strength characteristic
Figure 2 shows the early hour strength of CLSM after casting for different mixtures. The strength mainly attributes to the matrix skeleton effect of cement hydration products. The existence of much free water provides conditions for the good flowability of fresh mixtures, while it prolongs the condensation and solidification, and hinders the development of its early strength. Therefore, for the common CLSM ($\beta=0\%$), the early strength is 0 for specimens with different $\alpha$. The accelerator can promote the rapid hydration reaction of the cementitious material, make the fresh mixture solidify and form the early bearing capacity. For the case of $\beta=40\%$, the early hour strength develops fastest at $\alpha=0.13$, which is due to the total amount of cementitious material and the internal free water content. When $\alpha$ is 0.07 and
0.10, the hydration product cannot form a strong skeleton structure; and when $\alpha$ is 0.15, the reduction of construction waste causes the decrease of free water absorbed, resulting in the increase of free water inside the fresh material, which is harmful to the formation of early strength.

When $\alpha$ (0.13) and $\gamma$ (0.28) are constant, the 2-4 hours strength of CLSM at the concentration of 20%, 30%, and 40% of accelerator reaches 0.14-0.27MPa, 0.26-0.73MPa and 0.41-0.79MPa, respectively. However, the 4-hour strength at 50% is only 0.13MPa, since the excessive accelerator generates insufficient hydration products for the content mismatch of CaO and SiO$_2$ [19]. When $\alpha$ (0.13) and $\beta$ (40%) are fixed, the increase of $\gamma$ (0.27-0.30) leads to the increase of free water inside the fresh mixture, and it takes more time to coagulate and solidify, thereby attenuating its early strength properties.

The rapid-hardening properties of CLSM can accelerate construction progress and save construction costs. Referring to ACI 229R [5], the strength of backfill compacted soil is about 0.3~0.7MPa. Meanwhile, the CLSM minimum strength required in most applications is 0.345MPa to ensure that can support the construction personnel load [8]. Therefore, the subsequent process can be carried out when the CLSM strength reaches 0.345MPa for the road base backfilling. For the accelerator content of 40%, when $\alpha$ is 0.13 or 0.15, the basic bearing capacity can be satisfied after 2 hours of pouring.

3.2.2. Long-term strength

The strength with different ratios at curing age 1d, 3d, 7d, 14d, 28d, 56d and 91d were tested and the results are shown in figure 3. From figure 3(a), it can be seen that the strength of common CLSM increased with the increase of $\alpha$ and curing age, and the strength of 91d can reach 2.16-7.55MPa. The variation of strength with age was faster in the early period and then slowed down, which is consistent with the characteristics of the cement hydration reaction. The excavation strength range of CLSM is 0.3-2.1MPa [5]. So for the pipeline backfilling project, $\alpha$ should not be greater than 0.07.

For the case of $\beta$=40%, the change of CLSM strength is similar to that of common type (see figure 3(b)), while it should be noted that the long-term strength with same $\alpha$ is slightly higher than the latter, indicating that the accelerator has a constant promoting effect on the long-term strength development. That is, when the design strength is fixed, the addition of accelerator can properly reduce the total amount of cementitious materials.

From figure 3(c), the strength of CLSM increased first and then decreased with the increase of accelerator content at the same age, and the strength with 40% accelerator was smaller than that of 30%, which is mainly because 40% accelerator promotes the early hydration reaction of the binder, resulting in a relative insufficiency of later hydration products. For the case of $\beta$=50%, the strength of 91d was less than 2MPa, which is related to the insufficient content of SiO$_2$ needed for later hydration reaction due to the excessive amount of accelerator.
According to figure 3(d), there is a negative correlation between the strengths of different ages and γ. This is due to the increase of the free water content in the CLSM, and more capillary pores were formed during the hardening process, which attenuate its strength.

When CLSM is applied to base course and sub-base of flexible pavement, its strength requirement is 2.8-8.3MPa [5]. So for the CLSM designed in this study, α should not be less than 0.10 to ensure sufficient bearing capacity. CLSM with strength of 1-4MPa can be used as a permanent pedestrian plaza [8]. Considering both of mechanical properties and economy, α is preferred as 0.07 or 0.10.

![Figure 3](image)

**Figure 3.** Long-term strength of different mixtures

### 3.3. Strength prediction based on BP neural network

#### 3.3.1. BP neural network and model building

The long-term strength of CLSM is affected by many factors, which is extremely difficult to establish a model by using the traditional formula fitting method for its complex relationship. However, BP neural network has a good fitting effect especially when dealing with complex nonlinear problems, so it is widely used in many fields [2, 20].

The general steps for establishing a neural network model are as follows: determining the number of network structure layers, selecting the number of hidden layer neurons and determining the network transfer function. According to related research [3], a typical three-layer network structure can complete any mapping from n to m dimensions. Therefore, this study uses a three-layer network structure that includes a hidden layer.

The CLSM strength prediction model is established based on four factors (α, β, γ and t), so the input layer nodes number is 4, and the output layer nodes number is 1. The choice of hidden layer nodes is complicated. In general, the empirical formula (1) is used to determine the number of neurons in the hidden layer.
\[ M = \sqrt{n - m} + n \]  \hspace{1cm} (1)

where: \( M \) — the number of hidden layer nodes; \( n \) — the number of input layer nodes; \( m \) — the number of output layer nodes. So the number of hidden layer neurons selected in this model is 6.

\[ S(x) = \frac{1}{1 + e^{-x}} \]  \hspace{1cm} (2)

The Sigmoid function (see formula (2)), which is commonly used in BP neural network, is employed as the transfer function in the network structure in this study. The Sigmoid function has a good effect on the fitting of nonlinear problems, and its threshold is \((0, 1)\), so it is necessary to normalize the inputs.

Based on the selected parameters above, a BP neural network structure model is established, as shown in figure 4.

**Figure 4.** Network structure model

### 3.3.2. Model training and prediction

This study relies on the BP neural network module in MATLAB software to establish the prediction model. To prevent over-fitting, all sample data are automatically divided into three parts (the training set, the validation set and the test set) before training. During training, the training model data is used to train the model. Each time the training is performed, the system inputs the data in the verification sample data set into the neural network model for verification, thereby obtaining an error. The system then uses this error to correct the weights of the model, so that the model is approached by multiple epochs. The test sample data is used for the final performance test to verify the reliability of the model.

**Figure 5.** Performance (Best validation performance is 0.48656 at epoch 19)

From figure 5, it can be seen that the training achieves the best effect after 19 epochs, after which the continuous 6 epochs of the mean square error (MSE) no longer fall, so the training stops. At this point, the MSE between the simulated and actual values of the validated sample data is 0.48656. Figure 6(a)(b)(c) demonstrate the regression relationship between the target values of the three data set samples and the model output values, and figure 6(d) shows the relationship of all data representations. Figure 6
signifies that there is a high consistency between the target value of CLSM strength and the output value, and the correlation coefficient is above 0.90. The high prediction accuracy indicating that training and prediction of the strength values based on the BP neural network is feasible; this can provide a good reference for the mix-design of CLSM.

Figure 6. Regression of target and output strength

4. Conclusions
Construction waste mainly comes from the civil infrastructure construction or building demolition. The internal heavy metal or radioactive material content is extremely low, so the prepared CLSM will not cause secondary pollution to the environment and pose a hazard to the human body in engineering application.

The increase of $\alpha$ and $\gamma$ promoted the flowability, but the mechanism is different, and the latter is more significant. For narrow backfill projects, $\gamma$ should not be less than 0.28 to ensure good filling. Rapid-hardening CLSM are prepared based on sprayed concrete accelerator. The strength of 2-4 h can reach 0.41 to 0.79MPa, which meets the requirement of rapid construction. The long-term strength of CLSM was influenced by multiple factors such as $\alpha$, $\beta$, $\gamma$ and $t$. The strength prediction model based on the BP neural network is established, which has high precision and good reliability, and can assist the mix-design.

Considering the engineering properties of CLSM in this study, it can be concluded that the preparation of CLSM from red brick construction waste is feasible and conducive to sustainable development. It is recommended that $\alpha$ should not be greater than 0.07 for projects which may be excavated later. For projects requiring strict construction time, 30-40% accelerator may be added. A
large amount of mixing water provides excellent flowability for fresh CLSM, while reducing its mechanical properties, so that a suitable mixing ratio needs to be designed for different projects.

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