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Research Article

Factors Affecting the Mechanical Properties of Cement-Mixed Gravel

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A study has been conducted to investigate the mechanical properties of cement-mixed gravel using the unconfined compression test and the tensile test. Basic factors including the curing period, the water-binder ratio, the cement content, and the strain rate were evaluated. Ordinary Portland cement with fly ash was employed as the cementation agent for preparing cemented samples. The results indicate that the unconfined compressive strength, the deformation modulus, and the tensile strength increase with the increase in the curing period. The ratio of tensile strength to unconfined compressive strength has no distinct change after 7 days. An optimum water-binder ratio can be obtained. The unconfined compressive strength and deformation modulus decrease as the water-binder ratio decreases and increase from the optimum water-binder ratio. With the increasing of the cement content, the unconfined compressive strength increases distinctly, the deformation modulus increases significantly when the cement content is less than 4% and then increased slowly, and the failure strain increases to a peak value and then decreases. With the increasing of the strain rate, the unconfined compressive strength increases slightly and the deformation modulus increases slowly. The failure strain decreases with an increase in the strain rate.

1. Introduction

Cement-mixed gravel or cement-stabilized aggregate is a new building material that takes advantage of natural sand gravel, discarded soils, or problematic soils and is compacted by adding a certain content of cement and water. Its strength and stiffness is significantly affected by compaction conditions and the type of stabilizers, such as cement, gypsum, and lime, varies for different soils [1, 2]. The strengths of these cement-stabilized materials significantly increase by increasing the amount of cementing agent. The density of cement is generally less than 90 kg/m^3, which is substantially less than the density of concrete [3]. Cement mixed with gravel is energy-efficient and eco-friendly. This type of material has been applied to abutments, cofferdams, dams, slopes, and mining [4–7]. The mechanical behaviour of these materials is therefore a continuing issue in the field.

Haeri et al. [8] have investigated the stress-strain and strength characteristics of cemented soils using triaxial, direct shear, unconfined compression, Brazilian, resonant column, and plane strain tests. Clough et al. [9] conducted Brazilian and unconfined compression tests and triaxial tests to examine the behaviour of cemented sand. The results indicated that peak strength and stiffness increased with an increase in density and cement content. The grain shape and grain arrangement have an important role in the behaviours of cemented sands. Kongsukprasert et al. [10] performed a series of drained triaxial compression tests on a well-graded gravel of crushed sandstone. They indicated that the strengths and the modulus increase with an increase in content of the cement and gravel. With an increase in the water/cement ratio (water-binder ratio) and period, the stiffness and the compressive strength rapidly increased; however, this effect has no distinct influence on the volumetric strain and axial strain. Saidi et al. [11] suggest that the uniaxial strength and deformation modulus of poorly consolidated granular rocks significantly increase with an increase in cement content. For low cement content, the uniaxial strength appeared to be sensitive to grain size, whereas the deformation modulus was insensitive for all values of cement content. Amini and

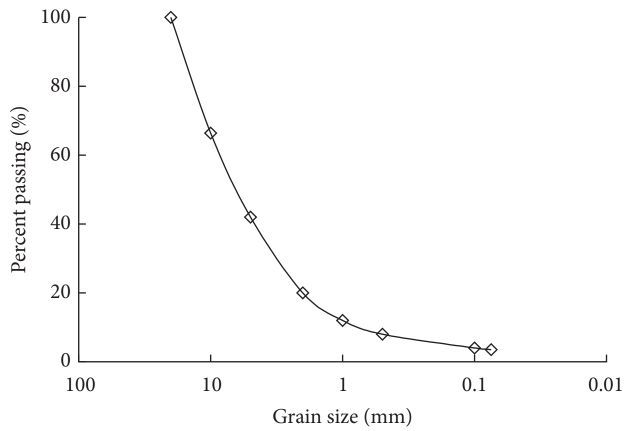

FIGURE 1: Grain size distribution of gravel.

Hamidi [12] performed large-scale triaxial compression tests to examine the behaviours of poorly graded sand-gravel mixtures in both consolidated drained and undrained conditions. Compared with the results of the undrained tests, the failure strain of the drained tests is lower and the brittle behaviour was more distinct. For the same experimental conditions, the peak shear strength of the poorly graded cemented gravely sand is lower than the peak shear strength of the well-graded cemented gravely sand. Taheri et al. [13–15] performed a set of single-step loading triaxial compression tests and multiple-step loading triaxial compression tests to examine peak strength and stress-strain properties of cement-mixed well-graded gravelly soil. Das and Dass [16] performed a set of direct tension tests, Brazilian and unconfined compression tests, on lightly cemented sand. The results indicate that the tensile strength σ_t and unconfined compressive strength σ_c increase with an increase in the cement content.

The literature review shows that some general factors of the behaviour of cement-mixed gravel have been conducted. However, few studies have focused on special factors, such as strain rates. The majority of the studies discuss cemented sand, whereas few studies discuss coarse-grained materials. In this study, detailed factors affecting the mechanical behaviour of cement-mixed gravel were researched. A series of unconfined compression tests and direct tensile tests were performed on unsaturated compacted specimens; the results are presented in this paper.

2. Materials and Methods

2.1. Specimen Preparation. The test soils were artificial broken limestone with specific gravity $G_s = 2.78$. Particles larger than 20 mm were removed. The grain size distribution is shown in Figure 1. The stabilizer is a mixture of Portland cement and fly ash (*the ratio* = 1 : 1).

The specimens were prepared by mixing gravel with a prescribed amount of cement and fly ash powder; they were subsequently mixed with a relevant amount of water. The compacted dry density ρ_d was 1.97 g/cm^3. Each specimen was manually compacted in five layers in a cylindrical mould (100 mm in diameter and 200 mm in height) with a controlled thickness of compacted layer of 40 mm, and the compaction energy level was controlled by the standard proctor (= 550 kJ/m^3). The time from the first mixing to the sealing in the mould was controlled within half an hour. The specimen was cured inside the mould for 24 hours with constant water content. Then, the specimen was removed from the mould and stored in hermetic plastic bags for additional curing.

2.2. Testing Methods. The unconfined compression tests and direct tensile tests were performed for cement-mixed gravel. Cylindrical specimens with a diameter (d) of 100 mm were produced with a height (h) of 200 mm according to $h/d = 2$.

Unconfined compression tests were performed with different water-binder ratios, cement contents, curing periods, and strain rates. All experiments were performed under strain controlled loading conditions, and the axial strain was measured using two dial indicators. To avoid pieces of the specimens falling off, they were covered with a layer of rubber membrane when testing. The unconfined compression tests were carried out according to the specification of soil test [17].

Several researchers investigated the tensile strength of cemented sand using the Brazilian test as it is easy to measure [18]. However, for cement-mixed gravel, particle size has a significant impact on the results of the Brazilian test. Therefore, the tensile strength of the cement-mixed gravel was obtained using the direct tensile test. The tensile apparatus was refitted with the unconfined compression apparatus, as shown in Figure 2. There were thread holes at the top of the loading cap and the lower end of the measure ring; they were connected with a thread rod. Prior to testing, the specimens and tensile device were cemented together with epoxy resin adhesive and cured for eight hours to ensure that the epoxy resin adhesive can be completely cured. The direct tensile tests were carried out according to the specification of soil test [17].

3. Results and Discussion

3.1. Effect of Curing Period. To evaluate the effect of curing period on the unconfined compressive strength, tensile strength, and the stress-strain behaviour, the unconfined compression test and direct tensile test were conducted. Two sets of specimens were cured for different periods under similar conditions. Specimens were compacted at dry density $\rho_d = 1.97$ g/cm^3, cement content by mass $\alpha = 4.2\%$, and water-binder ratio $w/b = 0.90$. The rates of axial deformation were 0.828 mm/min for the unconfined compression tests and 0.1 mm/min for the direct tensile tests, respectively. Three specimens for each condition were tested. The following results were obtained:

(1) Figure 3 presents the typical axial stress-axial strain behaviours for different curing periods at the unconfined compression condition. The prepeak stress-strain behaviour tends to become more linear with the increase in the curing period T. With an increase in strain, the stress increases towards the peak value and the specimens enter the plastic deformation phase. As the part of specimen began to slip, the capacity of

(a) For preexperiment

(b) For postexperiment

Figure 2: Direct tensile test using modified CBR.

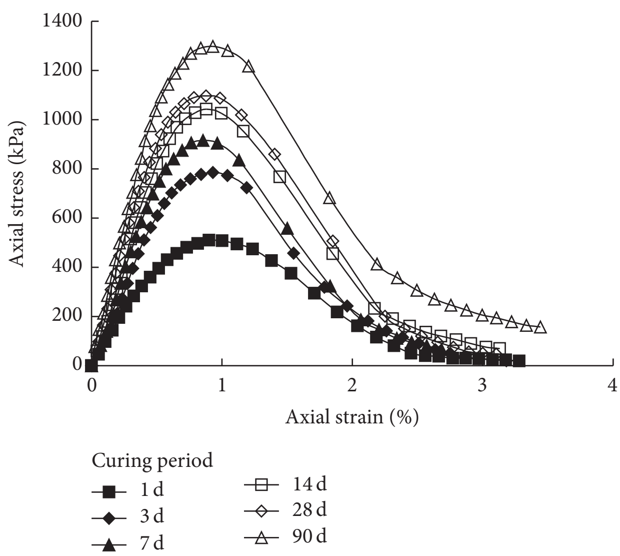

Figure 3: Axial stress-axial strain relationship for different curing periods at the unconfined compression condition.

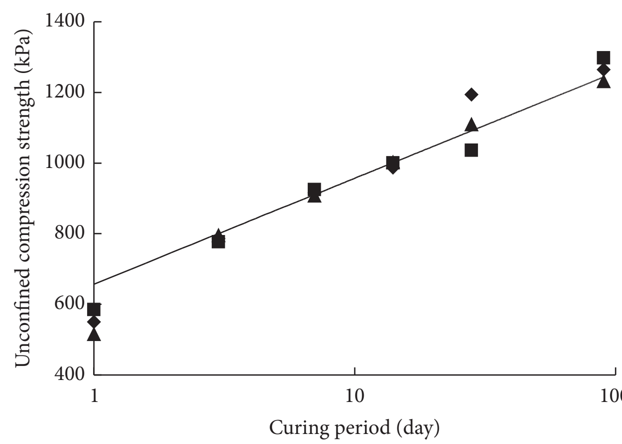

Figure 4: Relationship of unconfined compressive strength-curing period.

bearing loading began to decline and tended to be the residual strength.

(2) The unconfined compressive strength σ_c increases with an increase in the curing period T, which is linear with T on semilog coordinates, as shown in Figure 4. Because the unconfined compressive strength σ_c rapidly increases with an increase in T prior to 28 days and slowly increases after 28 days, the unconfined compressive strength after curing for 28 days is adopted as a reference strength, which is similar to the concrete [19]. The relationship between σ_c and T can be expressed as

$$\sigma_c^T = A^T \sigma_c^{28} \log \frac{T}{T_r} + B^T, \tag{1}$$

where σ_c^{28} is the unconfined compressive strength after curing for 28 days, $T \geq 3$ d, T_r is the relative curing period, $T_r = 28$ d, A^T and B^T are the material parameters, $A^T = 0.27$, and $B^T = 1091$ kPa.

(3) As the initial tangential modulus of cement-mixed gravel is difficult to measure, the secant modulus at the point of $\sigma = 0.5\sigma_c$ was employed as the deformation modulus E_0. The deformation modulus rapidly increased with an increase in T prior to 28

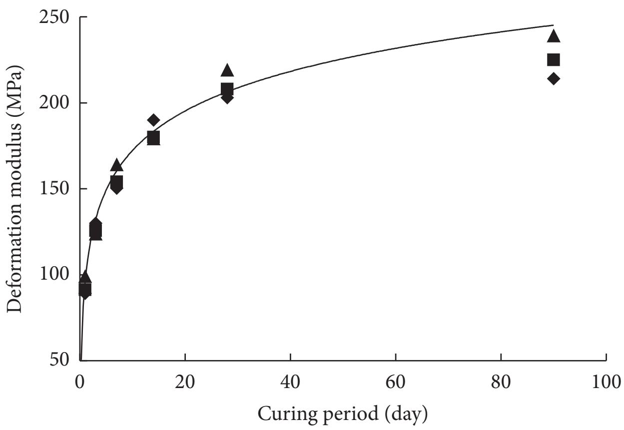

Figure 5: Relationship of deformation modulus-curing period.

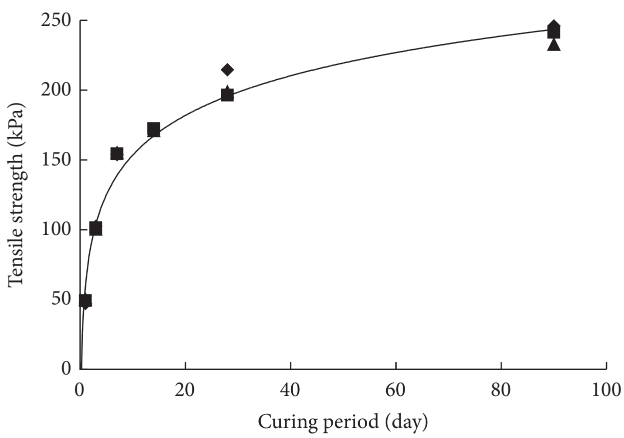

Figure 6: Relationship of tensile strength-curing period.

days; after 28 days, the deformation modulus slowly increases, as shown in Figure 5. The change in failure strain ε_f with an increase in the curing period was not distinct.

(4) The tensile strength σ_t increased with an increase in T; this increase is notable even after 28 days, as shown in Figure 6. The ratio of tensile strength to unconfined compressive strength σ_t/σ_c increased with an increase in T prior to 7 days; after 7 days, this ratio has no distinct change, as shown in Figure 7. The creation of cracks at the failure of the specimens for the unconfined compression test and the tensile test differ: in tension, the main crack path is horizontal, whereas the crack paths are inclined and initiated at the upper boundary in compression, as shown in Figure 8. In addition, the crack in tension abruptly appears with almost no secondary cracks along its path, whereas numerous secondary cracks are produced during crack growth in compression.

3.2. Effect of Water-Binder Ratio. The effect of the water-binder ratio w/b on the unconfined compressive strength, the

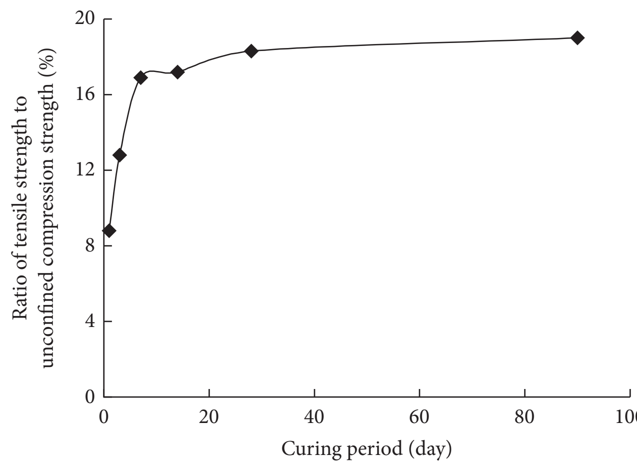

Figure 7: Relationship of ratio of tensile strength/unconfined compressive strength-curing period.

deformation modulus, and the failure strain were precisely evaluated with a small increment of w/b for the range from 0.5 to 1.5. Unconfined compression tests were performed on a series of specimens that were compacted at $\rho_d = 1.97\,\mathrm{g/cm^3}$, $\alpha = 4.2\%$, and $T = 28$ days. The rate of axial deformation was 0.828 mm/min. The following behaviour trends are observed:

(1) The effect of w/b on the unconfined compressive strength σ_c is significant. The maximum value of σ_c is obtained when w/b is similar to the optimum water-binder ratio $(w/b)_{\mathrm{opt}}$, as shown in Figure 9.

(2) The σ_c decreases as w/b decreases and increases from $(w/b)_{\mathrm{opt}} = 0.74$. The decreasing rate with a change in $w/b < (w/b)_{\mathrm{opt}}$ is larger than the decreasing rate with a change in $w/b > (w/b)_{\mathrm{opt}}$.

(3) The variation of the deformation modulus for different water-binder ratio is shown in Figure 10. The inflection point on the curve indicates that the deformation modulus E_0 increases before $(w/b)_{\mathrm{opt}} = 0.74$ and decreases after $(w/b)_{\mathrm{opt}} = 0.74$. This behaviour trend of E_0 is very similar to the trend of σ_c.

(4) Compared with the behaviours of σ_c and E_0, the change in failure strain rapidly increases at low w/b and remains relatively steady, as shown in Figure 11.

3.3. Effect of Cement Content. To research the effects of cement content (*cement/fly ash* = 1 : 1) on the unconfined compressive strength, deformation modulus, and failure strain of cement-mixed gravel, the unconfined compression tests were performed. A series of specimens were compacted to a constant dry density ρ_d ($1.97\,\mathrm{g/cm^3}$) with $\alpha = 2\%$ to 10% at $w/b = 0.90$ and $T = 28$ days. The rate of axial deformation was 0.828 mm/min.

The unconfined compressive strength σ_c approximately increases with an increase in the cement content, as shown in Figure 12. This trend is distinct, and even a cement content of 10% was attained. The increasing rate of E_0 with α is only significant until α is approximately 4%; subsequently, the rate

(a) For compression (b) For tension

Figure 8: Failure patterns.

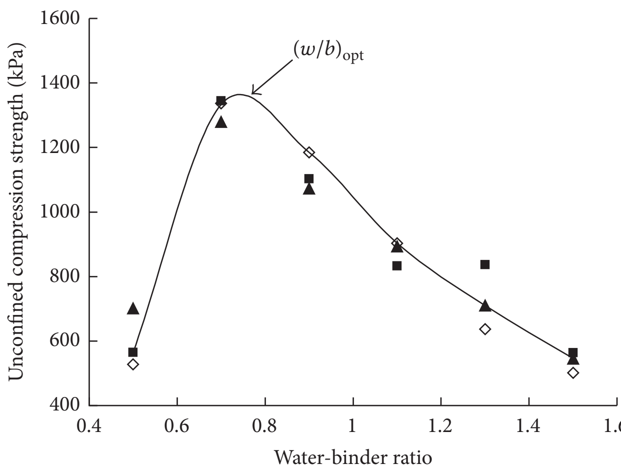

Figure 9: Variation of unconfined compressive strength for different water-binder ratios.

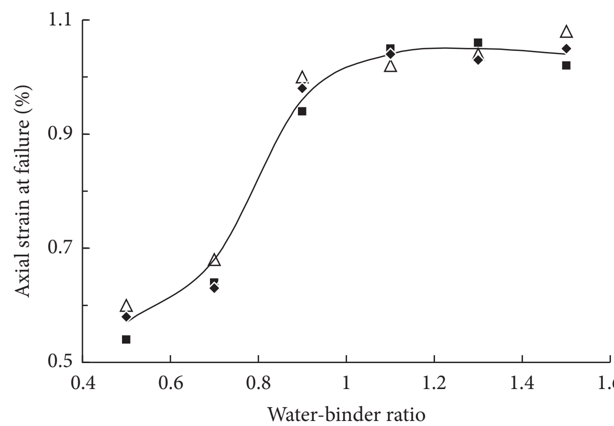

Figure 11: Variation of failure strain for different water-binder ratio.

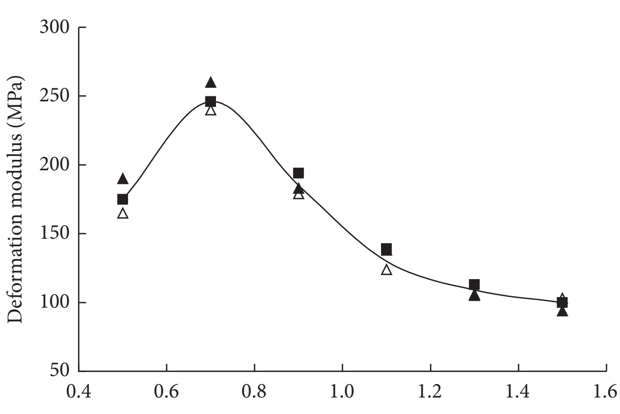

Figure 10: Variation of deformation modulus for different water-binder ratios.

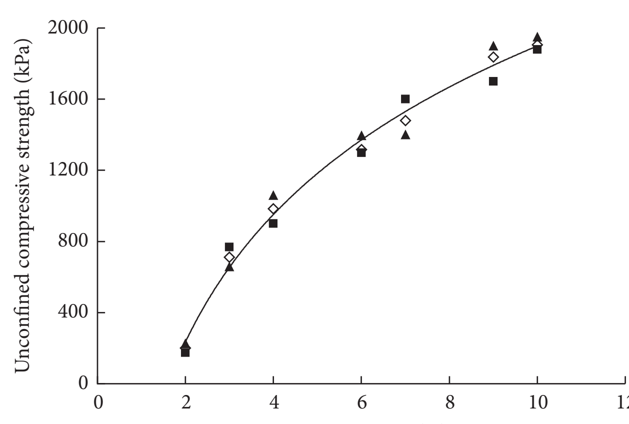

Figure 12: Variation of unconfined compressive strength for different cement content.

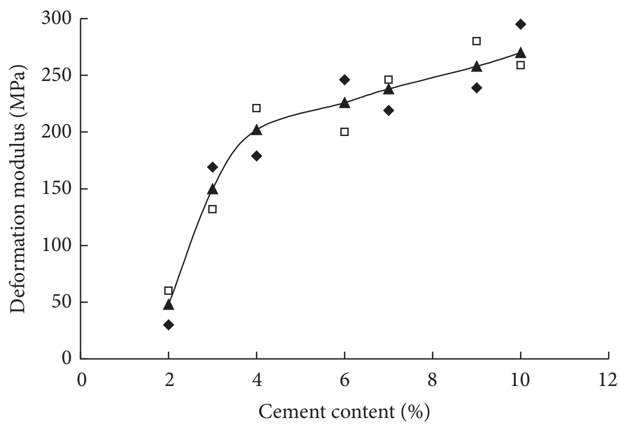

Figure 13: Variation of deformation modulus for different cement contents.

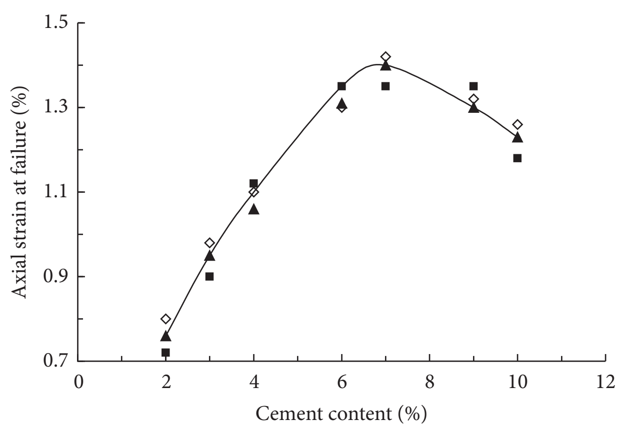

Figure 14: Variation of failure strain for different cement contents.

of increase decreases, as shown in Figure 13. The effect of α on the failure strain ε_f is distinct. ε_f increases when $\alpha < 7\%$ and subsequently begins to decrease, as shown in Figure 14. The range of ε_f extends from 0.7% to 1.5% in the test.

3.4. Effect of Strain Rates. To evaluate the influence of the strain rate $\dot{\varepsilon}$ on the unconfined compressive strength, deformation modulus, and failure strain of cemented mixed-gravel, the unconfined compression tests were performed under the different strain rates from $3.5 \times 10^{-4}\ \mathrm{s}^{-1}$ to $5.5 \times 10^{-7}\ \mathrm{s}^{-1}$. Specimens were compacted at $\rho_d = 1.97\ \mathrm{g/cm}^3$, $w/b = 0.90$, $\alpha = 4.2\%$, and $T = 28$ days.

Test results of the unconfined compression test for cement-mixed gravel at different strain rates are listed in Table 1. It can be seen that the unconfined compressive strength σ_c presents an increasing trend with an increase in strain rate; however, the trend is not distinct. The deformation modulus E_0 increases with an increase in strain rates with a trend of slow growth. The failure strain decreases with an increase in the strain rates.

Table 1: Experimental data of cement-mixed gravelly soil at different strain rates.

Test number	T (d)	$\dot{\varepsilon}$ (s^{-1})	σ_c (kPa)	ε_f (%)	E_0 (MPa)
T28-1	28	3.5×10^{-4}	1050	0.74	301.2
T28-2	28	6.9×10^{-5}	1040	0.80	250.4
T28-3	28	1.4×10^{-5}	1032	0.85	215.7
T28-4	28	2.8×10^{-6}	1021	0.94	189.6
T28-5	28	5.5×10^{-7}	1009	0.99	156.5

4. Conclusions

A series of unconfined compression tests and tensile tests were performed to investigate the mechanical behaviour of cemented mixed-gravel. From the test results presented in this paper, the following conclusions were obtained:

(1) The unconfined compressive strength increases linearly with an increase in the curing period on semilog coordinates. The deformation modulus significantly increases with an increase in the curing period before 28 days; after 28 days, the deformation modulus slowly increases. The tensile strength increases with the curing period. The ratio of tensile strength to unconfined compressive strength increases with an increase in curing period prior to 7 days; after 7 days, this ratio has no distinct change.

(2) An optimum water-binder ratio is obtained. The unconfined compressive strength and deformation modulus decrease as the water-binder ratio decreases and increase from the optimum water-binder ratio. The change in failure strain rapidly increases at low water-binder ratio and remains relatively steady.

(3) With the increasing of the cement content, the unconfined compressive strength increases distinctly, the deformation modulus increases significantly when the cement content is less than 4% and then increases slowly, and the failure strain increases to a peak value and then decreases.

(4) With the increasing of the strain rate, the unconfined compressive strength increases slightly and the deformation modulus increases slowly. The failure strain decreases with an increase in the strain rate.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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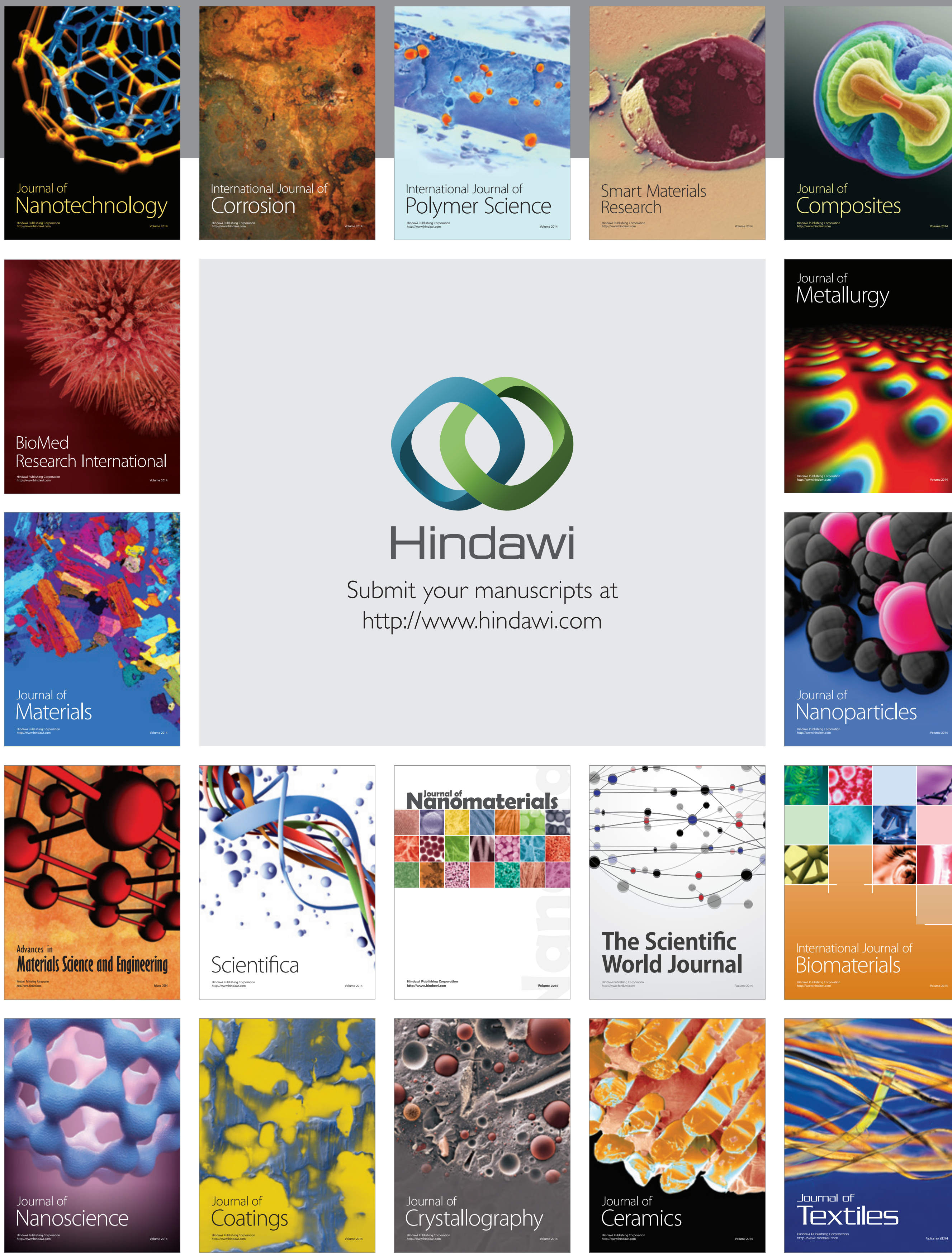
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