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Mechanical properties of recycled fine glass aggregate concrete under uniaxial loading

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Abstract. This paper reports the results of an experimental study on the compressive strength and the stress-strain curve (SSC) of recycled fine glass aggregate concrete with different replacement percentages of recycled fine glass aggregate. The results show that the recycled fine glass aggregate contents have significant impact on the workability, compressive strength, the elastic modulus, the peak and the ultimate strains of recycled fine glass aggregate concrete. Analytical expressions for the stress–strain relationship of recycled fine glass aggregate concrete are given, which can satisfactorily describe the effect of the recycled fine glass aggregate on the SSC.

Keywords: recycled fine glass aggregate; concrete; mechanical properties; stress-strain curve; uniaxial loading

1. Introduction

Glass waste is a highly durable material and it is highly resistant to most natural environments. As a result, disposal of used glasses is a major concern as inappropriate disposal can lead to signifi-cant environmental and aesthetic problems. Hence, recycling of waste glasses has become a cri-tical issue worldwide. Following the implementation of various EU directives, reuse and mat-erial recovery are considered as the most environmentally viable ways for managing waste mate-rials.

The use of waste glass as aggregates in concrete has been studied by several other researchers (Dhir *et al*. 2004, Dhir *et al*. 2003, Jin *et al*. 2000). Their works were carried out to examine the Possibility of reusing waste recycled glass in concrete and establish solid ground for clear under-standing and further investigation. Since the recovered waste glass is adopted as the main raw mat-erial, the recycle of resource is realized, the environment is protected, and the cost is saved.

Schmidt and Asia (1963) first investigated the potential risk of alkali-silica reaction (ASR) in concrete with the presence of recycled glass as an aggregate replacement.

Pattengill and Shutt (1973) examined that the possibility of using very fine grounded powdered

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glass as pozzolanic material to replace the cement. Taha B and Nounu G (2009) found that no major difference in compressive strength of concrete with the presence of recycled glass sand (RGS) as sand replacement, and the use of RGS as sand replacement in concrete possesses high risk of ASR expansion. And they proposed several methods to mitigate the ASR expansion, such as the replacement of cement by pozzolans, addition of fibers, and the addition of lithium compounds. But Saccani A and Bignozzi MC (2010) found that severe ASR would not occur for glass sand concrete. Fabio Paiva Cota *et al.* (2015) studied mechanical properties and ASR evaluation of concrete tiles with waste glass aggregate. Chiou *et al.* (2014) explored the effects of adding waste glass and sewage sludge on sintering behavior and performance of the aggregates. Tang (2014) applied Taguchi optimization technique in determining process condition for producing synthetic lightweight aggregate by incorporating waste thin film transition liquid crystal displays (TFT-LCD) glass powder with reservoir sediments.

The effect of replacement of coarse and fine aggregates or even cement by recycled waste glass on the fresh and mechanical properties of concrete or cementitious composites has been reported. Kiang Hwee Tan and Hongjian Du (2013) found that use of waste glass particles as fine aggregates would reduce the flowability and density of mortar, but increase its air content. Except drying shrinkage, the mechanical properties were compromised due to micro-cracking in glass sand and weakened bond with the cement paste. Arul *et al.* (2015) evaluated the performance of fine recycled glass as a supplementary material in blends with cement stabilized recycled concrete aggregate. Vitoldas *et al.* (2014) found glass powder as complete replacement for quartz powder and silica fume would improved micro-structural and compressive strength properties of ultra-high performance concrete. Gerry Leea *et al.* (2013) found the concrete blocks containing fine glass aggregates showed higher water absorption and lower hardened density than the control concrete block. Roz-Ud-Din Nassar and Parviz Soroushian (2012) studied that milled waste glass was used as secondary cementitious material towards production of recycled aggregate concrete with improved strength and durability attributes. Kima *et al.* (2014) found that the incorporation of WGS as a partial replacement for cement had beneficial effects on the compressive strength of concrete, especially when used together with fly ash. Ali *et al.* (2014) found that UPV value increased and transport properties were improved with the increasing recycled glass aggregate content. Yasser *et al.* (2013) investigated the effect of glass replacement with fine aggregate on the Self Compacting Concrete properties. However, the influence of glass sand on the stress-strain relation has rarely been reported.

In this study, experiments are performed to provide a comprehensive experimental and analytical evaluation of the stress–strain relation of recycled fine glass aggregate concrete with different recycled fine glass aggregate contents in compression. The influences of recycled fine glass aggregate on the peak stress and the peak strain, the shape of the stress–strain curve, and the elastic modulus are analyzed. An analytical expression is given to describe the complete stress–strain relation of recycled fine glass aggregate concrete in terms of the fine glass aggregate contents. The results presented in this paper are significant to efficiently use the fine glass aggregate contents in practical applications.

2. Research significance

2.1 Materials

Table 1 Physical properties of natural coarse aggregates

Grading (mm)	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Volume porosity (%)	Silt content (%)	Crushing value (%)
5-25	1610	2650	39.4	0.23	8.2

Table 2 Physical properties of river sand

Fineness modulus	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Silt content (%)
2.6	1460	2570	1.56

Table 3 Physical properties of recycled fine glass aggregate

Grading (mm)	Apparent density (kg·m^{-3})	Bulk density (kg·m^{-3})	Closed density (kg·m^{-3})	Porosity (%)
0~5	2460	1620	2100	36

Table 4 Mix proportion of the waste glass fine aggregate concrete

Index	Glass content (%)	W/C	Glass (kg·m^{-3})	Cement (kg·m^{-3})	Sand (kg·m^{-3})	Stone (kg·m^{-3})	Water (kg·m^{-3})
w-0	0	0.43	0	453	720	1286	195
w-20	20	0.43	144	453	576	1286	195
w-40	40	0.43	288	453	432	1286	195
w-60	60	0.43	432	453	288	1286	195
w-80	80	0.43	576	453	144	1286	195
w-100	100	0.43	720	453	0	1286	195

Ordinary Portland Cement with a 28d compressive strength of 42.5 Mpa was used in this inve-stigation. The coarse aggregate used was natural coarse aggregates, which in the range 5-25 mm.

The used fine aggregates were river sand and recycled fine glass aggregate obtained from waste glass brought from the reclamation depot in Nanchang, PR China. Table 1 lists the physical properties of natural coarse aggregates. Table 2 lists the physical properties of river sand. Table 3 li-sts the physical properties of recycled fine glass aggregate.

2.2 Mix proportions

Table 4 provides the design of the concrete mix. Researchers prepared a total of six different concrete mixes using water-cement ratio of 0.43. The main difference between these mixes is the waste glass fine aggregate replacement percentage, which is 0%, 20%, 40%, 60%, 80% and 100%, respectively. In the case of a waste glass fine aggregate replacement percentage equals 0%, the concrete is the normal concrete, which served as the reference concrete.

2.3 Mixing, casting and curing

The preparation and the cure of all the mixes were conducted in the State Key Laboratory for

Concrete Material Research at East China Institute of Technology in Nanchang, PR China. All mixing was conducted under laboratory conditions. The dry cement and aggregates were mixed for 1min in a 0.05m^3 laboratory mixer. The mixing continued for further 1 min while about 70% of water was added. The mixing was continued for another 1 min and the slump test was run to determine its workability. For each mix, total of three 100×100×100 mm cubes, six 100×100×300 mm prisms. After 24 h, the specimens were demoulded and cured in a fog room (20±2^{o}C, 95% relative humidity) for 28 days. The cube specimens were used to obtain the cube compressive strength and the prism specimens were used to obtain the stress–strain curves of the recycled fine glass aggregate concrete.

2.4 Testing

All specimens were tested according to Standard for test method of mechanical properties on ordinary concrete in china (GB/T 50081-2010) after 28 days. The loading setup was a YAW-3000 microcomputer controlled electro-hydraulic servo tester as shown in Fig. 1. In order to get the complete stress-strain curves, the drift rate of the test specimens was kept constant to 0.3 mm/min. During the experiment, the axial compression and the vertical deformation of the test specimens were automatically collected by the computer installed.

Fig. 1 Test setup

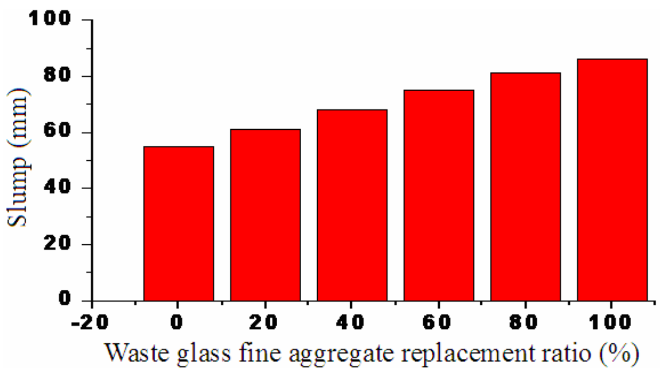


Fig. 2 Slump of concrete

3. Results and discussion

3.1 Concrete workability

Workability of concrete is measured with the slump test. Fig. 2 shows the slump of concrete. It is shown that the concrete slump rises significantly as the fine glass aggregate replacement per-centage increases. When the waste glass fine aggregate replacement percentage is 100%, the slump is 1.56 times that of ordinary concrete. Because the waste glass surface is smooth, com-posed of its and other aggregate mortar can play a roll bead and lubrication in coarse aggregate , re-ducing the friction between the coarse aggregate, so the liquidity of waste glass fine aggregate con-crete is bigger, so as to increase its slump.

3.2 Compressive strength

The compressive strength test was used to determine the failure stress of the test specimens under uniaxial compression. The prisms compressive strength f_c and the cube compressive strength f_{cu} of recycled fine glass aggregate concrete with different waste glass aggregate replacement percentages are given in Table 5. It can be seen from Table 5 that the compressive strength of recycled fine glass aggregate concrete decreases with the increase of waste glass aggregate replacement percentages. The f_c and f_{cu} of recycled fine glass aggregate concrete are lower than that of the normal concrete. Except in the case of w-100, the f_c/ f_{cu} ratio of recycled fine glass aggregate concrete is higher than that of ordinary concrete. The average f_c / f_{cu} ratio of recycled fine glass aggregate concrete is 0.78, which is 2% higher than that of ordinary concrete.

Table 5 Compressive strengths and elastic modulus

Index	f_c (Mpa)	f_{cu} (Mpa)	f_c / f_{cu}	E_c(×10^4 Mpa)
w-0	25.78	34	0.76	3.13
w-20	25.36	32.1	0.79	3.11
w-40	25.2	30.5	0.82	3.02
w-60	23.3	29.7	0.78	2.89
w-80	22.3	28.6	0.78	2.76
w-100	19.2	26.3	0.73	2.66

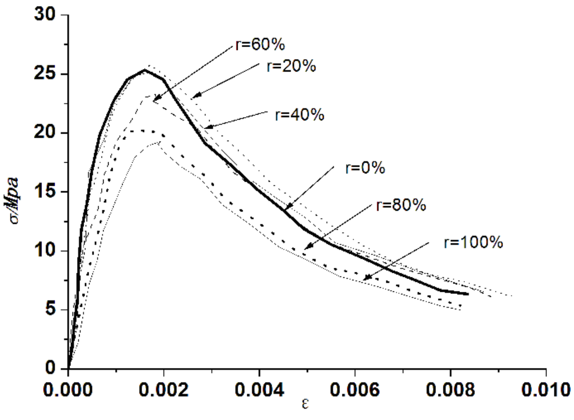


Fig. 3 Typical stress-strain curves of glass fine aggregate concrete

3.3 Elastic modulus

Table 5 presents the modulus of elasticity results of all test specimens. It can be seen that the modulus of elasticity varies in the same way as the compressive strength and decreases with the increasing percentage of substitution of fine glass aggregates. When the waste glass fine aggregate replacement percentage is 100% , the elastic modulus is reduced by 15.2%.This is the consequence of the application of the fine glass aggregates concrete with a lower elastic modulus than that of the natural fine aggregates.

3.4 Stress-strain curves

Fig. 3 shows the typical stress–strain curves of glass fine aggregate concrete with different glass fine aggregate contents. It can be seen that the glass fine aggregate replacement percentage has remarkable influences on the stress–strain curves of glass fine aggregate concrete. Nevertheless, all the concretes present very similar stress-strain curves regardless of the recycled aggregate replacement ratio. It is worth mentioning that the glass fine aggregate concretes develop strains which are higher than the strains achieved with the conventional concretes under the same unit stress mainly due to the lower elastic modulus of the glass fine aggregate concrete. And the higher the replacement percentage is, the higher they will be. Roughly speaking, the stress–strain curves of glass fine aggregate concrete can be divided into three characteristic parts. The first part represents the linear portion and the second represents the nonlinear portion of the ascending branch, and the third part is the descending branch.

With the increase of the glass fine aggregate content, it allows the increase of curvature of each ascending branch of the glass fine aggregate concrete. Consequently this increase leads to an increase in the peak strain value which is particularly significant when the recycled aggregate is used with a replacement ratio of 100%. The surface properties and the shape of the glass fine aggregate may also have influences on the stress-strain curves and the elastic modulus.

Another notable fact of the stress-strain curves of glass fine aggregate concrete is that the shape of the descending branch is also similar for concretes with different glass fine aggregate content. Also the slope of their descending branch decreases when the percentage of recycled fine aggregates is increased. In conclusion, the addition of glass fine aggregate into a normal concrete leads to a substantial change in its stress–strain responses. This change is that the peak strain (strain at peak stress) increase is especially significant when the replacement percentage of conventional fine aggregate with fine glass aggregate reaches 100%. Another change is a significant decrease in the ductility of the concrete as described by the descending portion of the stress–strain curves of glass fine aggregate concrete.

3.5 Peak strain

The values of the peak strain (at the peak stress) have been identified for the different concretes. Fig. 4 shows the peak strains of the glass fine aggregate concrete with different fine glass aggregate contents. It can be seen that the use of recycled fine glass aggregate increases the values of peak strain, and the higher the replacement percentage is, the higher they will be. When the fine glass aggregate replacement percentage r=100%, the peak strain is increased by about 21%. The main reason for the increase of the peak strain of recycled fine glass aggregate concrete is due to the reduced elastic modulus of fine glass aggregate concrete, which leads to a larger deformation.

Based on the analysis of many related test results and a data regression, Nicolo (1994) proposed an approximate formula for the peak strain of the normal concrete

$$\varepsilon_0^n = 0.00076 + [(0.626 f_c^n - 4.33) \times 10^{-7}]^{0.5} \tag{1}$$

For the glass fine aggregate concrete, we suggest the following empirical formula for calculating the peak strain

$$\varepsilon_0^g = 0.00034 r^{0.6059} + \varepsilon_0^n \tag{2}$$

where ε_0^g is the peak strain of glass fine aggregate concrete, *r* is the glass fine aggregate concrete replacement percentage. Comparisons of the experimental and the predicted values of peak strain by Eq. (2) presented in Fig. 5 show that Eq. (2) fits the experimental results satisfactorily.

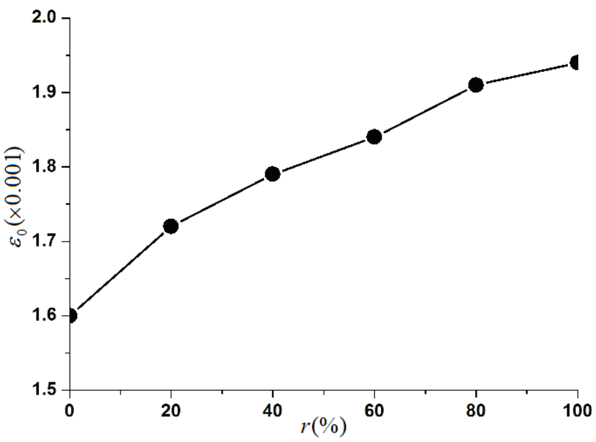


Fig. 4 Peak strain of glass fine aggregate concrete

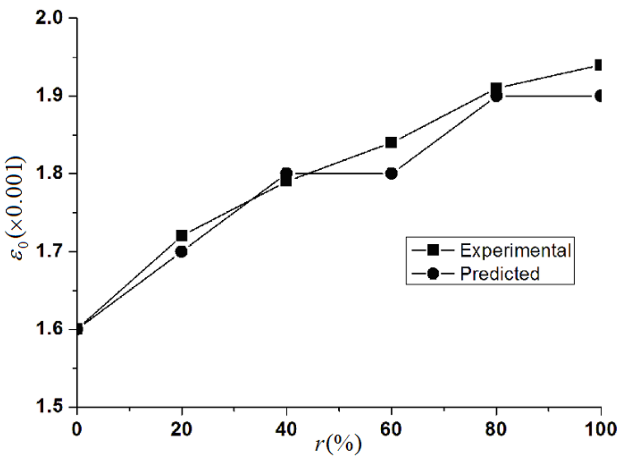


Fig. 5 Comparison of the peak strain

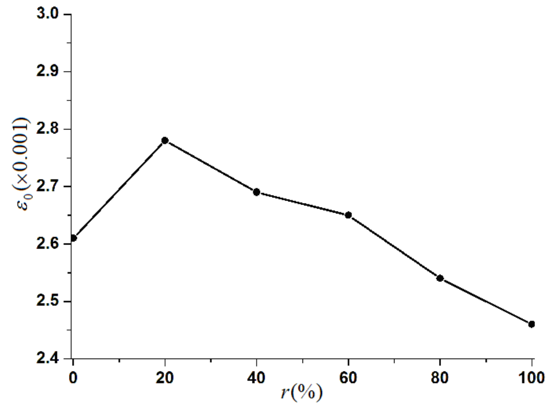


Fig. 6 Ultimate strain of glass fine aggregate concrete

3.6 Ultimate strain

The ultimate strain is taken as the longitudinal strain at a stress level equals to 85% of the peak stress. Fig. 6 shows the ultimate strains of the glass fine aggregate concrete with different fine glass aggregate contents. It can be seen that with the increase of glass fine aggregate replacement percentage, the ultimate strain of glass fine aggregate concrete may decrease or increase, depending on the value of the fine glass aggregate replacement percentage *r*. For a small value of *r* the ultimate strain increases with increasing *r*, while the opposite may be the case for a large value of *r*.

4. Approximation of the stress-strain relations

A form of model equation for the stress-strain curve of conventional concrete has been suggested by many researchers (Hognestad *et al*. 1995, Yi *et al*. 2003, Wee *et al*. 1982). In this study the analytical expression suggested by Guo and Zhang (1982), adopted by Chinese Code GB50010 (2010), for uniaxial compression of normal concrete is used. This equation is extended in this study to glass fine aggregate concrete. The normalized stress–strain relation of glass fine aggregate concrete is approximated by the following equation

$$y = \begin{cases} ax + (3-2a)x^2 + (a-2)x^3, 0 \le x < 1 \\ \dfrac{x}{b(x-1)^2 + x}, x \ge 1 \end{cases} \tag{3}$$

In Eq. (3), $x = \varepsilon / \varepsilon_0$, $y = \sigma / f_c$, *a* and *b* are constants to be determined. The parameter *a* is the slope of the initial tangent of the dimensionless stress-strain curve, which reflects the initial elastic modulus of glass fine aggregate concrete. The smaller the *a* -value is, the smaller is the proportion of the plastic deformation at the peak stress with respect to the total deformation. The parameter *b* is related to the area under the descending portion of the dimensionless stress-strain curve. The larger the *b*-value is, the steeper is the descending portion, and the smaller is the ductility of the glass fine aggregate concrete.

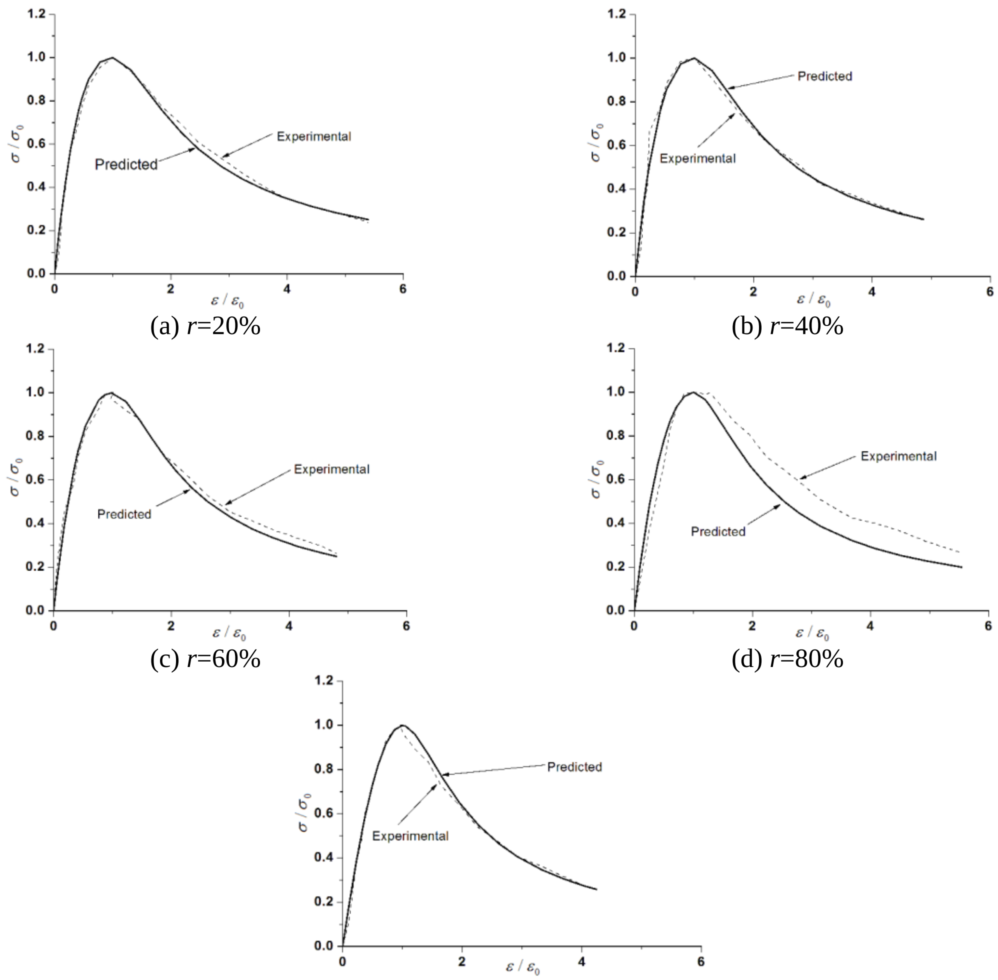
Based on the experimentally obtained stress–strain curves of glass fine aggregate concrete, the parameters *a* and *b* were obtained by a data regression analysis. The results are given as follows

$$a = -1.45r^2 + 0.66r + 2.65 \tag{4}$$

$$b = 0.41r + 0.75 \tag{5}$$

where *r* is the glass fine aggregate replacement percentage.

In Figs. 7(a)-7(e), a comparison between the experimentally obtained and the approximated stress-strain curves provided by Eq. (4) is shown for different values of the replacement percentage r. The approximate stress-strain curves agree quite well with those obtained experimentally. Hence, the approximate stress-strain relations for the fine glass aggregate concrete can be used in practical engineering applications.



(a) *r*=20% (b) *r*=40%

(c) *r*=60% (d) *r*=80%

(e) *r*=100%

Fig. 7 Comparison of the normalized stress–strain curves

5. Conclusions

Based on the experimental results, the following conclusions can be drawn

- The slump of fine glass aggregate concrete rises as the waste glass fine aggregate replacement percentage increases.
- The compressive strength of recycled fine glass aggregate concrete decreases with the increase of waste glass aggregate replacement percentages. The modulus of elasticity varies in the same way as the compressive strength and decreases with the increasing percentage of substitution of fine glass aggregates.
- The shape of the stress-strain curves of fine glass aggregate concrete is similar to that of conventional concretes. The addition of glass fine aggregate into normal concrete leads to substantial change in its stress-strain curves. The stress-strain curves of fine glass aggregate concrete indicate an increase in the peak strain and a significant decrease in the ductility as characterized by their descending portion.
- The use of recycled fine glass aggregate increases the values of peak strain, and the higher the replacement percentage is, the higher they will be. When the fine glass aggregate replacement percentage r=100%, the peak strain is increased by about 21%.
- The analytical expression initially proposed by Guo and Zhang for normal concrete was extended to fine glass aggregate concrete in order to obtain approximate stress-strain curves of fine glass aggregate concrete, which can be used directly in many practical engineering applications of fine glass aggregate concrete.

Acknowledgments

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