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Performance Degradation of the Repeated Recycled Aggregate Concrete with 70% Replacement of Three-generation Recycled Coarse Aggregate

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Abstract: The feasibility of using different generations recycled coarse aggregate (RCA) on structural concrete was fully evaluated by studying the performance of the recycled coarse aggregates and their corresponding concretes, the different generations of RCA were recycled by following the repeated mode of ‘concrete-waste concrete-coarse aggregate-concrete’. Moreover, the focus was on ‘three generations’ of repeated RCAs, the RCA was produced by crushing and regenerating the artificial accelerated degraded concrete, the process was designed to follow the nature degradation of the concrete with a coupling action of accelerated carbonation and bending load. The properties of x-generation (x=1, 2 or 3) of repeated RCA were systematically investigated and the compressive and splitting tensile strengths of relating structural concretes(with 70% replacement of x-generation of RCA) were studied accordingly. The results show a competent compressive and splitting tensile strength of 30 MPa at 28th day of structural concretes with all generations of repeated RAC. And the gradual degraded performance of the repeated RCAs was observed with an increased numbers of repetition (1>2>3 generations), the overall performances of all repeated RCAs fulfill the Class Ⅲ according to Chinese Standards GB25177-2010. Our gained insight demonstrates a feasibility of using at least 3 generations of repeated RCA for the production of normal structural concrete.

Key words: repeated recycled concrete; repeated recycled coarse aggregate;coupling action; compressive strength; ordinary atmosphere environment

1 Introduction

According to official statistic report[1], the annual demand and exploited natural aggregates (sand and gravel) for the production of concrete are over 10 billion tons in China. The rapidly increased demand of natural aggregate does lead to a scarcity of high quality natural aggregate in some big cities of China[1]. Meanwhile, the annual output of waste concrete, deriving from the retrofitting and reconstruction of the buildings, reaches 100 million tons and is expected to reach up to 638 million tons in 2020[2]. Nowadays, most of the demolished concrete is treated as normal waste and deposited into the landfill, which greatly increases the environmental and economical loads. Thus, it will be of great importance both economically and environmentally if we can find a feasible way to replace natural aggregates using waste concrete.

In order to improve the sustainable use of waste concrete, it has been reported a primary use for temporary access to roads in construction sites and as subbase course for road construction, however, such application was kept in a low efficiency level[3]. With increasing demand and shortage of natural aggregate, there is a need to develop a more effective way for recycling the waste concrete as an identical application in construction industries, especially, the recycled coarse aggregate (RCA) from waste concrete as a candidate of natural coarse aggregate (NCA) for structural concrete[3,4]. There are several studies that reveal a positive trend of such RCA used in the recycled aggregate concrete (RAC)[5]. However, the mechanical and durability performances of reported RAC are generally lower than that of conventional concrete, mainly due to the quality and replacement ratio of RCA to NCA[6-8]. The variable quality of RAC

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often relies on the sources, and RCA replacements of 25%-40% and 50%-70% were found byVivian WY Tam *et al*[3] to be optimal based on the strength and rigidity of RAC. Another interesting attempt is the recycling of the waste RAC as recycled coarse aggregate (repeated RCA), which will be an even more efficient and state of the art application in concrete industry. However, in our previous studies[9,10] and other works[11], the degradation properties of RCA were identified with the increase of recycling times, which is obviously adverse to the properties of concrete. Therefore, the effects of the degradation properties of repeated RCA on the structural behaviors of concrete have to be adequately investigated before considering the repeated RCA as the replacement for natural coarse aggregate (NCA) in actual structural concrete.

Even as a promising recycled material, repeated RCA and its RAC have been rarely reported from our best knowledge. There is a study from Sumaiya Binte Huda and M. ShahriaAlam[11], where the mechanical behavior of three generations of 100% repeated RCA concrete was studied and RCA was recycled 3 times over its life span. They successfully gained the target strength of 32 MPa for all mixes at the age of 120 days. However, at 28-day age, the strength of the RAC is lower than 32 MPa, and the repeated RCA was just produced by crushing recycled concrete specimens after a 56 days aging, and there is no consideration of the coupling action of load and environmental factors that the actual structural concrete is suffered. Overall, there is no systematical research on the repeated RCA. In this paper, a facile route was designed to investigate the coupling action of bending loads (40% splitting tensile strength of RAC specimens) and indoor accelerated carbonation on the RAC specimens that suffered several recycles (different generations). The nomenclatures of the 1, 2 and 3 generation recycled coarse aggregate are denoted as RCA1, RCA2 and RCA3, and 1, 2 and 3 generation recycled coarse aggregate concrete as RAC1,RAC2, and RAC3. According to the optimal replacing ratio of RCA[3], and the performance degradation of the 100% replacement[11],70% RCA was used to replace natural coarse aggregate in three generations of repeated recycled concrete.

It should be mentioned in particular that there is no quality standard available for recycled coarse aggregate for structural concrete in China. Chinese Standards GB/T25177-2010[12], "Recycled coarse aggregate for concrete" classifies recycled coarse aggregate into three types, *i e*, Class Ⅰ, Class Ⅱ, and Class Ⅲ, but does not point out which class is suitable for use in structural concrete. L Butler *et al*[13] summarized the current standard specifications from abroad for RCA for use in concrete, presented the quality requirements of RCA used in structural concrete, including that from BS[14], ASTM[15] and their own finding. These quality requirements, however, are not fully applicable to RCA produced in China, because of the huge quality variation resulting from regional differences *etc*[16]. Therefore, proper investigation about structural behavior of mechanical and durability properties of repeated RAC is highly demanded to make certain that which class of RCA can be used to produce structural concrete. The size graduation and properties of three generations (repeat recycling 3 times) RCA were investigated and evaluated, and their quality class was classified according to Chinese standards GB/T 25177-2010 in this study.

2 Artificial accelerated degradation for making waste concrete

Due to the unavailability, the repeated RCAs were prepared in lab via simulating the service condition of actual structural concrete in ordinary atmospheric environment in order to ensure the representation of the repeated RCAs. The ordinary atmospheric environment here refers to Type Ⅰ of five environment classifications in Chinese Standard GB/T 50476-2008[17], where carbonization is the main environmental factor affecting the property of structural concrete, and waste concrete from this environmental classification is very suitable for reuse. The simulation was based on the equal carbonation depth of concrete in ordinary atmospheric environment and in lab. For this purpose, the carbonization depth prediction model proposed by Xiao *et al*[18] was used, as shown in Eq.(1):

$$X_c=K_{CO_2}K_{K1}K_{KS}T^{0.25}R^{1.5}(1-R)(\frac{230}{f_{Cu}^{RC}}+2.5)\sqrt{t} \tag{1}$$

where the four environmental parameters, temperature T, relative humidity R, CO_2 concentration, and RAC compressive strength f_{cu}, and the load type, are considered.

Given the equal carbonation depth, one can gain the relationship between the accelerated carbonation days (d) in lab and natural carbonation years (a) in

Table 1 Chemical composition of the binders analyzed by XRF/wt%

Component	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	MnO	K_2O	TiO_2	SO_3	LOI
Cement	21.13	7.34	3.82	1.18	59.68	0.18	0.38	0.82	2.23	2.76
Fly ash	52.50	28.33	3.67	1.12	3.82	0.20	1.69	0.97	1.75	1.30
Slag	32.36	17.20	1.31	7.88	26.46	0.96	0.45	0.87	0.70	0.71
Silica fume	86.18	1.08	0.93	0.78	0.23	0.12	-	-	0.84	2.62

Table 2 Mix proportions of concretes/(kg/m^3)

Concrete tape	Cement	Slag	Fly ash	Free water	Silica fume	Additional water	Sand	Gravel	JK-PCA	PP	RCA
NAC	207	46	184	194	23	0	561	1 039	2.25	0.46	0
RAC1	207	46	184	194	23	16	561	312	2.25	0.46	727
RAC2	207	46	184	194	23	21	561	312	2.25	0.46	727
RAC3	207	46	184	194	23	23	561	312	2.25	0.46	727

ordinary atmospheric environment, see Eq.(2):

$$d=\left[\frac{K^{a}_{CO_2}T_{a}^{0.25}R_{a}^{1.5}(1-R_a)(230/f^{a}_{cu}+2.5)}{K^{d}_{CO_2}T_{d}^{0.25}R_{d}^{1.5}(1-R_d)(230/f^{d}_{cu}+2.5)}\right]^2 a \tag{2}$$

The ordinary atmospheric environment conditions of Nanjing city were considered in this study. T, R, CO_2 concentration were taken as 14.4 ℃ (annual average temperature), 76% (annual average relative humidity), and 0.04%, respectively.

In the present study, the coupling action of load and environmental factors was carried out to finish the simulation. The coupling action device presented by Jin *et al*[19] is chosen, consisting of a steel bending loading test device, where 30% ultimate tensile stress of concrete specimen is considered, and an accelerated carbonation chamber, where temperature, relative humidity, and CO_2 concentration are 20 ℃, (70±5)%, and 20%, respectively.Therefore, the corresponding parameters in lab were taken as 20 ℃ (average temperature), 70% (average relative humidity) and 20% (average CO_2 concentration percentage). And the ratio of cube compressive strength of RAC from lab to RAC from atmospheric environment was taken as 1.1:1 in terms of Chinese code GB50204-2002[20], *i e*, the service life of 50 years in atmospheric environment was chosen because it is usually used as the design life of civil engineering buildings in China.

Substitute the values of these parameters into Eq.(2) and let a=50 years, then d=17 days.

3 Experimental

3.1 Raw Materials

Four binders were used for the RAC preparation, which are ordinary Portland Cement 42.5 with a density of 3.12 g/cm^3 and a blaine specific surface area of 336 m^2/kg, fine ground slag with a specific surface area of 463 m^2/kg, class Ⅱ of fly ash with a specific surface area of 460 m^2/kg, and silica fume with a specific surface area of 2 473 m^2/kg, and the chemical compositions are listed in Table 1.

The natural coarse aggregates (NCA) were crushed dolomite with the nominal size of 5-20 mm, and natural sand (particle density about 2 680 kg/m^3) with nominal size of 0.36-4.75 mm was selected as fine natural aggregate (FNA).The first generation recycled coarse aggregate with the nominal size of 5-20 mm was collected from commercially recycled ones and came from the demolished concrete structural buildings serviced for about 50 years in the ordinary atmospheric environment.

Polycarboxylate superplasticizer (JK-PCA, made in Changzhou Institute of Building Science) and modified polypropylene fiber (PP) were used to increase the workability and strength of concrete respectively.

3.2 Mix proportion

The study is based on the Chinese standard GB/T 25177-2010 to determine the quality class of repeated recycled coarse aggregate and to compare their properties with that of natural coarse aggregates, and both of them are used together with natural fine aggregate (sand) for the production of 30 MPa structural concrete.

Mix proportion design of the natural aggregate concrete follows the Chinese Standards JGJ 55-2011[21], and that of all RACs are designed according to the method proposed by Zhang Yamei *et al*[22], where the dosage of additional water is considered by water absorption of RCA at 30 min. The details of all mix proportions are listed in Table 2.

3.3 Sample preparation

The present study evaluates the performance of first, second and third generation of RCAs and their compatiblization with structural concrete. 1st generation recycled aggregate concrete (RAC1) was produced by replacing natural coarse aggregate with 70% 1st generation recycled coarse aggregate (RCA1, 5-20 mm). After curing for 28 days at a standard curing (room temperature of (20±3) ℃ and relative humidity of more than 90%), RAC1 specimen was applied with a coupling action, the 150 mm^3 sample was fixed in a steel frame with a bending load of 40% ultimate tensile strength and the whole sample frame was placed afterwards into carbonization chamber for 17 days, and then the degraded concrete was used to produce 2nd generation repeated recycled coarse aggregate (RCA2, 5-20 mm) by means of the method proposed by Zhou *et al*[23]. Replacing natural coarse aggregate with 70% 2nd generation repeated recycled coarse aggregate(RCA2), 2nd generation repeated recycled concrete (RAC2) was produced and cured under the same condition for another 28 days, and then suffered the abovementioned coupling action for another 17 days, and then used as the source of 3rd generation repeated recycled coarse aggregate (RCA3, 5-20 mm)[23]. The RCA3 was used to produce the 3rd repeated recycled concrete (RAC3) with the replacements of natural coarse aggregate by 70% RCA3. The recycling yields of the RAC 1, 2 and 3 from waste concrete were 70%, however, the rest waste could also be used for recycled fine aggregate (RFA), so the waste concrete could be 100% recycled principally, this paper will focus on the coarse aggregate replacement, the further study of the RFA will be discussed in our future studies.

The coupling action was imposed according to the following process: fixing RAC specimens of 150 mmd as the source of 3rd generation, adjusting the spring through nuts on its upper end until the bending load equal to 40% ultimate tensile strength load of RAC specimen; then putting the steel frame along with RAC specimen into the carbonization chamber and lasting for 17 days.

4 Results and discussion

4.1 Gradation of coarse aggregate

The sieve analyses were performed according to Chinese Standard GB/T 14684[24] and GB/T 14685[25]. In the light of Chinese standard GB/T 25177-2010, the coarse aggregates used in the experiment display a good size gradations, all different generations of repeated recycled coarse aggregates fall within acceptable range of the GB/T 25177-2010 standard, as shown in Fig.1.

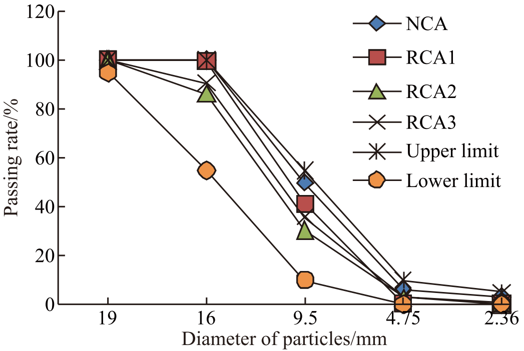

Fig.1 Gradation curves of natural coarse aggregate (NCA) and different generations repeated recycled coarse aggregates

4.2 Physical properties and microstructure of coarse aggregate

As comparison, the physical properties of different generations repeated recycled coarse aggregates and the natural coarse aggregates are presented in Table 3. The apparent density, water absorption, crushing index, and Na$_2$SO$_4$ soundness loss of all four different types of aggregates were tested in terms of Chinese standardGB/T 25177-2010. The apparent density of NCA was 2 673 kg/m^3, which was higher than that of recycled coarse aggregates. At the same time, the apparent density of repeated recycled coarse aggregate decreases with the repetitions of recycling, which is 2 621, 2 484, and 2 260 kg/m^3 for RCA1, RCA2 and RCA3,respectively (1.94%, 7.07%, and 15.45% smaller than that of NCA). The adhered mortar content was measured according to the thermal treatment method[26], which was found to increase with the number of recycling. The increased adhered mortar content results in a continuous decrease of the apparent density of repeated recycled coarse aggregate, and the lowest value appeared with RCA3. Water absorption of aggregate expresses its porosity. An interesting finding of this study reveals that the 24 h water absorption of RCA1, RCA2 and RCA3 was 4.9%, 4.1%, and 2.6%, respectively which was about 378.57%, 192.85% and 85.71% higher than that of NCA. The water absorption was not increasing with the number of repetitions as expected, in contrast with the studies by Sumaiya Binte Huda *et al*[11]. This may come from cement partly replaced by fly ash, silica fume, and slag. The crushing index and soundness of RCA stand for its crush resistance and rupture resistance, respectively. Both of crushing index and Na$_2$SO$_4$ soundness loss of the repeated recycled coarse aggregates increase when the number of repetitions increases, which means the decreasing of crush resistance and rupture resistance. The high

Table 3 Physical properties of coarse aggregates

Coarse aggregates type	Apparent density /(kg/m^3)	24 h water absorption/%	Crushing index/%	Na_2SO_4 soundness loss/%	Adhered mortar content/%
NCA	2 673	1.4	12.5	4.1	-
RCA1	2 621	6.7	14.3	4.7	37.7
RCA2	2 484	4.1	15.4	8.3	54.8
RCA3	2 260	2.6	17.3	17.2	61.9

values of crushing index and Na_2SO_4 soundness loss of the repeated recycled coarse aggregate are attributed to the increasing adhered mortar content. In fact, the increasing adhered mortar content leading to high porosity of RCA influences greatly the relevant property indexes such as the apparent density, crushing index, and Na_2SO_4 soundness loss.

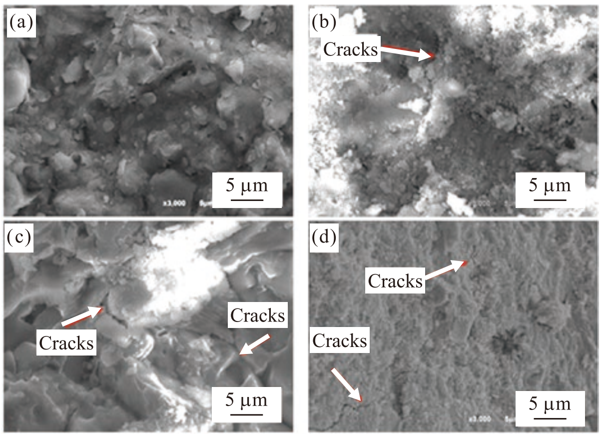

Fig.2 Morphology of coarse aggregates: (a) natural coarse aggregate (NCA); (b) 1st generation recycled coarse aggregate (RCA1); (c) 2nd generation recycled coarse aggregate (RCA2); and (d) 3rd generation recycled coarse aggregate (RCA3)

Fig.2 exhibits the morphology of four types of coarse aggregates. These pictures show that crack and defects extended along interface transition zones between recycled coarse aggregate and new and/ or old mortar when the number of repetitions increased. This indicates that the quality of repeated RCA descended with the number of repetitions which would have negative impact on all the performances of repeated RAC. The pore and crack, however, were not found in the case of natural coarse aggregate (NCA). The quality downward trend in the RCA with the number of repetitions is in consistent with that in other similar studies[9,10,11].

4.3 Properties of fresh concrete

The test results of slump and slump flow of different concretes are shown in Table 4. The slump value of natural aggregate concrete (NAC) was 148 mm which was a little bit higher than that of the target slump of 140 mm. This slump value was designed to delegate a more practical mix because in ready pump concrete mix the slump of 140 mm is usually taken when maximum pumping height is within 60 meters. The slump values of RAC1, RAC2 and RAC3 were 147, 143, and 132 mm respectively, which fell within a confined range of the target slump of 140 mm. The slump was found to drop with the increased number of repetitions. On the one hand, because of the addition of fly ash, silica fume, and slag, the absorption capacity of repeated recycled coarse aggregate reduced with the increased number of repetitions. At the same time, additional water was added for all of repeated recycled concrete according to water absorption of repeated recycled coarse aggregate at 24 h in order to maintain their workability. These two aspects have contributed to the improvement of the workability of repeated RAC. On the other hand, the roughness and angularity of repeated RCA increased with the increased number of repetitions, which can in no way help raising the slump value of repeated RAC. A decreased trend in terms of slump flow value was also observed with the increased number of repetitions. Table 4 shows that the slump flow values of NAC, RAC1, RAC2, and RAC3 are 2.47, 2.50, 2.53 and 2.33 times of their corresponding slump values, respectively, varying around 2.50 times.

4.4 Compressive strength of RAC

Table 4 Fresh concrete properties

Item	Slump/mm	Slump flow/mm
NAC	148	365
RAC1	147	368
RAC2	143	362
RAC3	132	307

The compressive strength tests results of four types of concrete mixes are displayed in Fig.3 for age of 28 days. It can be discovered that the continuous use of repeated RCAbrings about a reduction in compressive strength of the repeated RAC with repetitions. The compressive strength of RAC1, RAC2, and RAC3 were 39.3, 35.1, and 31.5 MPa, respectively which were approximately 6.7%, 16.6 %, and 25.2 % smaller than that of NAC. However, all the considered concrete batches achieved their target strength of 30 MPa at the age of 28 days. We attribute this to three aspects:a) the higher quality of repeated RCA, although all physical properties tested except for water absorption of different generations repeated recycled coarse aggregates showed a degradation trend, RCA1 and RCA2 belong to Class Ⅱ and RCA3 falls into Class Ⅲ in terms of Chinese standard GB/T 25177-2010. Compared with the quality requirements of RCA for structural concrete from BS[14] and ASTM[15], the RCA in Class Ⅲ of Chinese standard GB/T 25177-2010 seems to apply to the production of structural concrete; b) 70% replacement of repeated RCA to NAC, as mentioned above, this replacement is the optimum; and 3) the replacements of cement by fly ash, silica fume, and slag, and the addition of JK-PCA and PP, the replacement and addition result in the improvement of compressive strength of the repeated RAC.

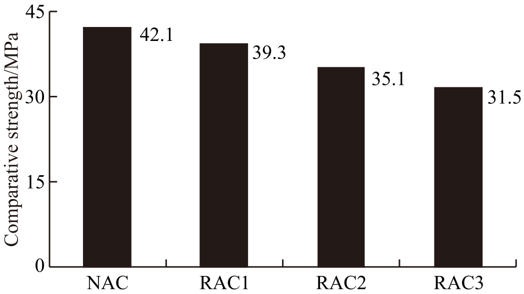

Fig.3 Compressive strength of various concrete mixes at 28 days

4.5 Splitting tensile strength of RAC

The splitting tensile strengths of four types of concrete at 28-day age are shown in Fig.4. It has been found in this study that the splitting tensile strengths of RAC1, RAC2, and RAC3 were 4.7, 3.9, and 3.4 MPa, respectively which were almost 7.8%, 23.5%, and 33.3% lower than that of NAC. This was attributed to the lower absorption capacity of repeated RCA caused by the use of fly ash, silica fume, and slag. Moreover, the subsequent use of repeated recycled coarse aggregate caused reduced splitting tensile strengths due to its lower quality and high porosity.

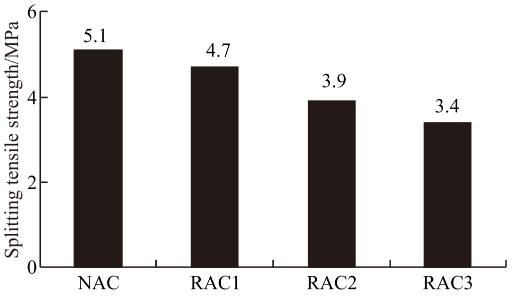

Fig.4 Splitting tensile strength of four types of concrete at 28 days

The results that all repeated RACs achieved the target strength and met the requirement of splitting tensile strength of 30 MPa at the age of 28 days declared that it is feasible to use repeated recycled coarse aggregate to produce structural concrete. There should be a maximum number of repetitions for concrete waste as coarse aggregate for structural concrete since the quality of repeated RCA decreased with the increased number of repetitions.

5 Conclusions

This study presents a feasible route to the usage of recycled concrete waste for the production of structural concrete by replacing part of natural coarse aggregate. The physical properties of the recycled aggregate and the relevant concrete performance were systematically studied. Based on our study, we can safely draw several conclusions:

a)The attached mortar content of different generations of repeated RCAs increased with increasing number of repetitions. The attached mortar content of RCA1, RCA2 and RCA3 were37.7%, 54.8%,and 61.9%, respectively.

b) The apparent density of RCA1, RCA2 and RCA3 were 1.94 %, 7.07%, and 15.45% lower than that of natural coarse aggregate, respectively.

c) The water absorption of different generations of repeated recycled coarse aggregates decreased with increasing number of repetitions due to the addition of fly ash, silica fume, and slag partly replacing cement.

d) Both of crushing index and soundness of the repeated recycled coarse aggregates increased when the number of repetitions increased, *i e*, the crush resistance and rupture resistance decreased.

e) All considered concretes achieved the target strength of 30 MPa at the age of 28 days.

f) The compressive strength of repeated recycled coarse concrete decreases as the number of repetitions increases.

g) The splitting tensile strength of RAC1, RAC2 and RAC3 were 7.8%, 23.5%, and 33.3% lower than that of natural aggregate concrete, respectively, but met the requirement of C30.

Differing from the existing research results related to repeated RCA and repeated RAC,we successfully solve the repeated RCA source problem and gain the target strength of 30 MPa at the age of 28 days. Although fully using repeated RAC to replace natural coarse aggregate in concrete will affect the performance of concrete greatly, we demonstrate that only using 70% replacement can produce very good C30 concrete, even using the lowest quality RAC, *i e*, using Class Ⅲ of Chinese Standard GB/T 25177-2010. This is a valuable finding, which proves a scientific and efficient approach of waste concrete towards the application in structural concrete.

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