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INFLUENCE OF VIBRATION ON PERFORMANCE OF RECYCLED CONCRETE

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ABSTRACT

In this study, the vibration mixing technology is researched, and the effect of the vibration on the performance of recycled concrete is investigated. Through the analysis of the strengthened mechanism on the recycled concrete adopting vibration mixing, the vibration could increase of collision numbers between aggregates so as to purify the surface of recycled aggregates, and improve the interface between the recycled aggregates and cement pastes, and realize the macroscopic and microscopic uniformity of recycled concrete to improve the performance of recycled concrete. The performance of recycled concrete mixed by ordinary forced mixing and vibration mixing respectively, was compared experimentally. And the results indicate that the vibration could increase the air contents of recycled concrete, improve the mechanical performance of the recycled concrete, provide a favorable environment in order to enhance the microscopic structure and strengthen the recycled concrete.

KEYWORDS

Forced mixing, Vibratory, Concrete performance, Recycled concrete

INTRODUCTION

The utilization of recycled concrete is one of the idealized ways to recycle the waste cement concrete. After the waste concrete is subjected to crushing, cleaning, and sieving, the substitute of the resulting recycled aggregates for new sandstone aggregates can realize the concrete preparation and thus realize recycling of such primary materials as sand, stone, etc. Since the recycled aggregate and natural aggregate possess different structures and properties, primarily the residual mortar is attached to the surface of recycled aggregates, and micro-cracks are present in the surface [1]; compared to the ordinary concrete, all these defects will lead to a lower apparent density, a higher porosity, a worse mobility, which results in the inferior mechanical behaviour of recycled concrete and inferior durability including chloride ion permeability, impermeability and freeze-thaw resistance [2].

So far domestic and international researchers launched a lot of investigations on improving the performance of recycled concrete, which were primarily focused on the improvement of material property and material preparation. Aiming at the characteristics of recycled aggregates, some researchers performed plastic processing on the recycled aggregate particles and immersed the aggregates into acid liquor to remove the attached mortar; then they immersed the aggregates into the sodium silicate solution and cement pastes to fill the pores and micro-cracks so as to improve the behaviour of recycled concrete [3]. Some researchers added some additives and mineral during the recycled concrete preparation in order to improve the behaviour; the additives were water reducing agent, which could compensate the quantity of free water absorbed by the residual mortar attached to the recycled aggregate so as to reduce the effect of free water on the behaviour of concrete [4]. The mineral additives are commonly fly ash and silica fume. Researchers found that the beads in the fly ash could fill pores and micro-cracks, and replace the water in the pores and micro-cracks to improve the strength and mobility of recycled concrete; the unique fineness and activity of silica fume could react with $Ca(OH)_2$ during the early hydration of cement to produce C-S-H gel filling the pore micro-cracks, which could then increase the strength of recycled concrete [5]. Several scholars suggested that according to the characteristics of recycled aggregate, the adjustment of the mix proportion could improve the behaviour recycled concrete [6]. The researches on preparation technologies were centred around the adjustment of the aggregates feeding order, mixing time, mixing velocity, and their combination of various technology parameters in order to improve the properties of recycled concrete. The most common preparation technology is the remixing technology of recycled concrete [7]. The different aggregate feeding orders and phased mixing could realize the full uniform mixture of each constituent; the hydrate covered the aggregates like a protection layer, which could effectively avoid the further contact between water and aggregate, and restrain the thickness of water film; the transitional layer with a low water cement ratio could allow the improvement of strength and behaviour of recycled concrete.

Aiming at the restraints of the recycled aggregate defects on the performance of recycled concrete, in this study, the feasibility to improve the behaviours of recycled concrete by the use of vibration mixing is investigated. The vibration mixing technology to prepare ordinary concrete is an efficient strengthened preparation method. The effect of this technology on the behaviours of recycled concrete is scarcely researched. In combination with the feature of recycled aggregates, the vibration mechanism on recycled concrete is researched; the comparative experiments are performed on the recycled concrete mixed by vibration and on ordinary concrete mixed by forced mixing; from the differences of marco-behaviours and microstrcutres of recycled concrete, the influence of vibration mixing on behaviours of recycled concrete are analysed.

STRENGTHENED MECHANISM TO IMPROVE THE BEHAVIOURS OF RECYCLED CONCRETE WITH VIBRATION MIXING

After the waste concrete subjected to crushing and sieving, the surfaces of recycled aggregates are present of residual mortar, and the mortar is unevenly distributed along the surface of aggregates. Pores and micro-cracks unavoidably exist in crushed recycled aggregates, as shown in Figure 1.

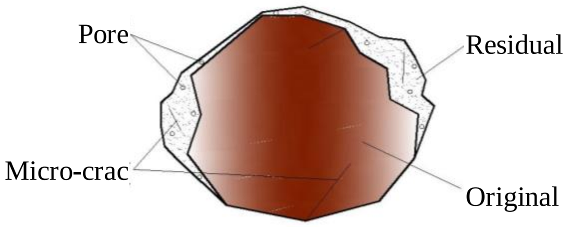

Fig.1 - Schematic diagram of recycled aggregate structure

During the preparation of recycled concrete, recycled aggregates, new aggregates, cement and water are proportionally placed into the vibration mixer, as shown in Figure 2. Under the action of mixing blades, in the 3-D mixing space comprising the axial and radial directions, a strong axial cyclic movement and a counter current movement between shafts will accrue to each constituent in the mixing pan. Each constituent can attain a macroscopic uniform mixing in a short time [8]. At the time of conventional mixing, the mixing shaft and blades exert vibration of a certain frequency to aggregates to force the aggregates in chattering states; the aggregates move in a large cycle and vibrate within a small range; the movements result in the increase of collision numbers between aggregates and contribute to purify the surface of recycled aggregates; during the early mixing, the vibration can immediately break the structures of cement agglomeration and water cluster to form smaller cement particles and water cluster particles, followed by the activation for the activity of cement particles and water, thus accelerating formation of the hydrate. During the later mixing, the vibration pressure wave due to the vibration accelerates the diffusion velocity of liquid-phase hydrate towards the surface of aggregates; meanwhile, the vibration breaks the bond between particles caused by microtubule pressures, and the cement pastes quickly cover the surface of aggregates, subsequently filling the micro-cracks of aggregates, improving the interface between the recycled aggregates and cement pastes and realizing the macroscopic and microscopic uniformity of recycled concrete so as to comprehensively enhance the behaviours of recycled concrete.

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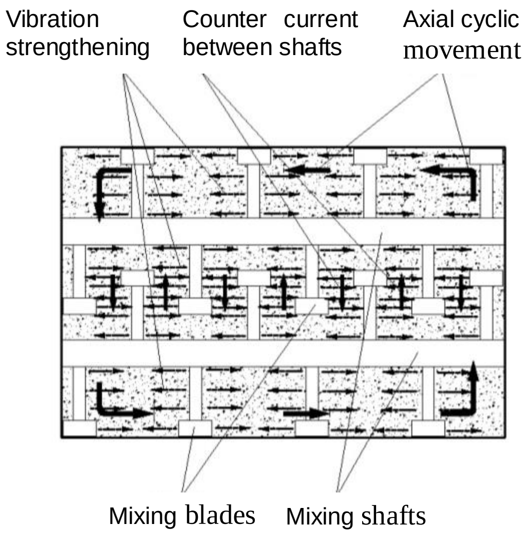

Fig. 2 - Strengthening mechanism of vibratory mixing of recycled concrete

EXPERIMENTAL PRIMARY MATERIALS AND MIX PROPORTION OF RECYCLED CONCRETE

The experimental cement is P.O32.5R Portland cement. The fine aggregate is common medium sand, whose apparent density is 2620kg/m3, and fineness modulus 2.89. The new coarse aggregate is continuously graded limestone with particle sizes of 5-25mm. The recycled aggregates come from waste C20, C30, C40 concrete; the recycled aggregates with particle sizes of 5-25mm are obtained by crushing and sieving the waste concrete as shown in Figure 3. The behaviours of recycled aggregates and new aggregates are given in Table 1. The mixing water is common tap water. No additives are used.

Fig.3 - Recycled aggregates

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Tab. 1 - Behaviours comparison between recycled aggregates and new aggregates

Aggregate type	Apparent density/ (kg/m^3)	Packing density/ (kg/m^3)	Porosity/ %	Crushing index/ %	Water absorption/ %
Recycled aggregate	2470.6	1354.6	45.2	17.0	7.1
New aggregate	2800.1	1611.7	42.4	6.1	2.4

The design strength of recycled concrete for tests is C30. Based on the frequently used aggregate contents, the percentages of recycled aggregates are selected as 0%, 25%, 50%, and the design slump is 10-30mm. The new mix proportion is obtained by adopting the actual water gel ratio of recycled concrete, as shown in Table 2.

Tab. 2 - Mix proportion of recycled concrete

Concrete strength	Amount of each constituent/(kg/m^3)					Percentage of recycled aggregates/ %
	Cement	Water	Fine aggregate	New aggregate	Recycled aggregate	
C30	391	180	657	1172	0	0
C30	388	198	651	872	291	25
C30	385	212	647	578	578	50

EXPERIMENTAL SETUP AND EXPERIMENTAL METHODS

Experimental setup

The double horizontal shaft vibration mixer was designed and manufactured by our research team. The mixer utilizes the independent mixing actuation and vibration actuation shown in Figure 4. The mixing actuating device can only drive the mixing shaft and blades to realize common mixing of the concrete; the vibration actuating device can force the mixing shaft and blades to vibrate; the simultaneous utilization of the mixing actuating and vibration actuating devices can realize a vibration mixing. The main parameters of the mixer are shown in Table 3.

Fig. 4 - Test mixer of vibratory mixing

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Tab. 3: Main parameters of the mixer

Volume/L	Number of mixing blades（single mixing shaft）	Design amplitude/mm	Vibration angular frequency/(rad/s)	Rotational speed of mixing blades/(r/min)	Linear speed/(m/s)
100	2+5(Return blade+propulsion blade)	1.2	185	50	1.47

Experimental methods

At the same testing conditions, the behaviours of recycled concrete with varying percentage of recycled aggregates are measured respectively by the use of ordinary forced mixing and vibration mixing. When tests prepared, the aggregate feeding order is recycled aggregate, new aggregate, cement, fine aggregate and water; the mixing time is 60s; the behaviour of the newly mixed concrete is obtained; after being cured in the same conditions, the mechanical behaviour of the concrete and micro-structures are also obtained. In accordance with *standard for test method of performance on ordinary fresh concrete* (GB/T 50080-2011), the apparent density, mobility, cohesiveness, water retention and air content are measured for fresh concrete to study the influence of vibration on the behaviours of fresh concrete. On the basis of *standard for test method of mechanical properties on ordinary concrete* (GB/T 50081-2011), the compressive strengths of 7d, 14d and 28d of recycled concrete test blocks, are measured to study the effect of vibration on the behaviours of recycled concrete. After the blocks are cut, scoured, polished, and dried, the processed blocks are then scanned by JSM-6390A, and the SEM diagrams of 500 and 6000 times are obtained to investigate the effect of vibration on the micro-structures of recycled concrete.

EXPERIMENTAL RESULTS

Influence of vibration on the behaviours of fresh recycled concrete

For different percentages of recycled aggregates, through ordinary forced mixing and vibration mixing, the average apparent densities of fresh concrete are shown in Figure 5, the average slumps shown in Figure 6, and air contents shown in Figure 7. From Figure 5, the apparent densities of recycled concrete mixed by the above mixing methods tend to a little decrease with the varying recycled aggregate contents. The apparent density of recycled concrete mixed by forced mixing drops by 3.75% for 0 aggregates and 50% aggregates, and the apparent density mixed by vibration mixing drops by 2.92%; for the same percentage of recycled aggregates, the apparent density mixed by vibration mixing is higher than that by forced mixing; when the percentage of recycled aggregates is 50%, the apparent density is 1.07% higher than that mixed by forced mixing, which indicates that the vibration mixing will bring about an obvious purification of aggregates surface; the vibration can reduce the internal frictions between aggregate particles; the cement pastes can fill the pores, micro-cracks in recycled aggregates and restrain the decrease of the apparent density for recycled concrete. From Figure 6, the recycled aggregates significantly influence the slump of recycled concrete. By the use of ordinary forced mixing, the slump loss is very fast with the increase of recycled aggregate contents, and the slump loss is 90% when the percentage of recycled aggregates is 50%; the vibration mixing can evidently improve the slump loss of recycled concrete, although the slump of newly mixed recycled concrete is 30% lower than that of ordinary concrete; however the slump of recycled concrete mixed by vibration mixing is the same as that of ordinary concrete mixed by forced mixing; the slump has no visible change when the percentage is 50%; this is because the vibration mixing destroys the structures of cement agglomeration and water cluster thus to form smaller cement particle and water cluster particle and increase the activity the cement particles and water, then leading to a sufficient hydration; the vibration mixing purifies the recycled aggregates surface, peels off some residual mortar, reduces the water absorbing capacities of recycled aggregates, increases the free water, reduces the slump loss of recycled concrete and improves the mobility. From Figure 7, compared to the recycled concrete mixed by ordinary forced mixing, the air contents of recycled concrete mixed by vibration mixing is obviously increased; for different percentages of recycled aggregates, the air contents are respectively increased by 66.7%,18.2% and 42.9%; the mixing of blades can wrap the big bubble into the aggregates, the vibration can decompose the big bubble into small bubble kept in the recycled concrete, further improving the air contents of recycled concrete, which can easily satisfy the engineering requirements for air contents. The increase of air contents in recycle concrete is a commonly adopted method to improve the durability of concrete [9]. Therefore, the vibration mixing can increase the air contents of fresh recycled concrete and can contribute to the improvement of concrete durability.

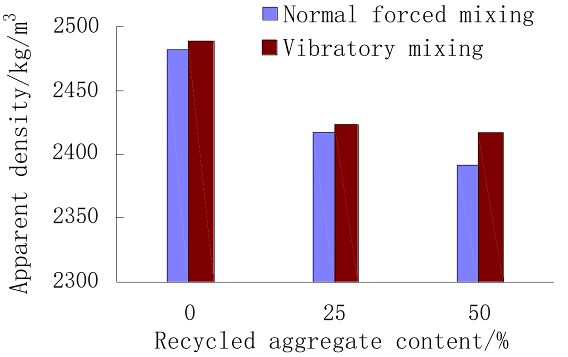

Fig. 5 - Apparent density of with different mixing methods

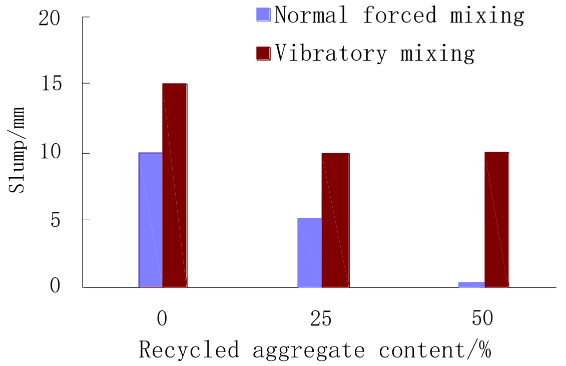

Fig. 6 - Slump with different mixing methods

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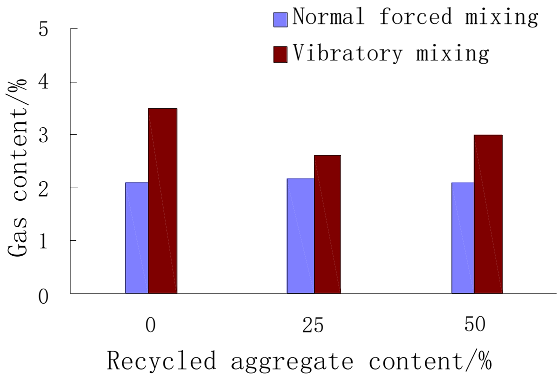


Fig. 7 - Air content with different mixing methods

Influence of vibration on the compressive strength of recycled concrete

For different percentages of recycled aggregates, the compressive strengths of 7d, 14d and 28d for hardened concrete with different mixing methods are shown in Table 4. From Table 4, in contrast to ordinary concrete without recycled aggregates, whether the recycled concrete is mixed by ordinary forced mixing or vibration mixing, the compressive strengths of recycled concrete blocks equally tend to fall; the compressive strength decreases with increasing the percentage of recycled aggregates. For 50% recycled aggregate content, the compressive strength of 28d for recycled concrete mixed by ordinary forced mixing is reduced by 23.4% and the compressive strength by vibration mixing is reduced by 24.2%. The compressive strength depends on the strength of aggregates, the strength of cement stone, and the bond strength of interface between them. Since the aggregate and cement stone have a higher strength, undoubtedly the failures frequently occur at the interface, which is the weakest location [10,11]. For recycled concrete, the interfaces of recycled concrete not only include the interfaces between the old aggregates and old cement paste, but also include the new interface between the new cement paste and old cement paste. With the increase of recycled concrete contents, the weak interfaces are more and more, and thus the recycled concrete is more susceptible to fail, which just illustrates the lower compressive strength of recycled concrete. For the same percentage of recycled aggregates, the compressive strength mixed by vibration mixing is higher than that by forced mixing. At 25% recycled aggregate content, the compressive strength of recycled concrete mixed by vibration mixing is 17.5% higher than that by ordinary forced mixing. At 50% recycled aggregate content, the compressive strength of recycled concrete mixed by vibration mixing is 12.1% higher than that by ordinary forced mixing. The vibration mixing can exert forced mixing and vibration energy to aggregates, the movement velocity of aggregate particles will increase and attain a macroscopic uniformity; in the meanwhile, the aggregates will be in a chattering state so that the collision of aggregate particles will purify the recycled aggregates surface, and spall some residual cement pastes; the vibration energy will destroy the cohesive structures of cement, the area of hydration will increase, the hydration products will increase, the movement velocity of hydration products attached to recycled aggregates surface will accelerate, and fill the pores and micro-cracks, to repair the recycled concrete, the bond strength and the compressive strength will be enhanced.

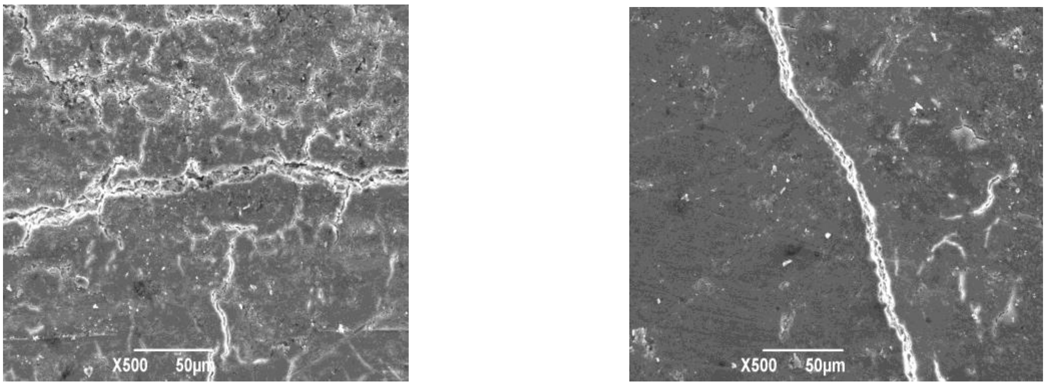
Tab. 4 - Compressive strength with different mixing methods

Percentage of recycled aggregate content/%	Ordinary forced mixing			Vibration mixing		
	7d Compressive strength/MPa	14d Compressive strength /MPa	28d Compressive strength /MPa	7d Compressive strength /MPa	14d Compressive strength /MPa	28d Compressive strength /MPa
0	20.77	23.34	28.56	21.85	26.76	32.36
25	18.65	20.35	22.23	19.25	23.98	26.94
50	17.10	19.89	21.88	17.86	21.79	24.53

Influence of vibration on the microstructures of recycled concrete

Through different mixing method, the recycled concrete with different recycled aggregate contents is cured for 28d. The SEM specimens of 8 mm×8 mm×5 mm are prepared by cutting apparatus; the specimens are subjected to scouring, polishing, and drying, and the specimens are sprayed with metal to ensure the conductivity. The SEM diagrams of 500 times and 6000 times for specimens are obtained as shown in Figure 8 and Figure 9.

The inherent pore cracks of recycled aggregates and the water absorbability of the residual mortar will give rise to difficult realization of microscopic uniformity of recycled concrete with the water cement ratio used in ordinary forced mixing. From Figure 8(a), in the identical curing conditions the microscopic hydration of recycled concrete specimens is not uniform by ordinary forced mixing method; the pores and cracks of concrete are densely distributed, composing series of big, medium and small cracks which are connected each other like a net, which will affect the strength of recycled concrete. It is indicated that the uniformity of microscopic water cement ratio is bad; under the action of ordinary forced mixing, the cement paste is present of cement agglomeration and water cluster; the water absorbing capacity of recycled concrete is a bit higher, and the water is transferred from cement pastes to recycled aggregates, which further leads to that the hydration reaction around recycled aggregates has a larger water cement ratio, and the region far from recycled aggregates has a smaller water cement ratio; thus the hydration velocities at each region is not uniform when the strength of concrete is initiated, and the inconsistent velocities will induce dense cracks. From Figure 8(b), the phenomenon of densely distributed pore cracks does not occur in the recycled concrete mixed by vibration mixing; the hydration of concrete surface is uniform and compact, which indicates that the vibration can break cement agglomeration and water cluster; the hydration of cement paste is sufficient and the microscopic water cement ratio is of recycled concrete is uniform; during the curing process, the consistent hydration velocity can thus improve the strength of recycled concrete, which can avoid the phenomenon of dense cracks. From Figure 9, the microscopic interface of recycled concrete mixed by vibration mixing is more tight than that by ordinary forced mixing; the granular and cluster C-S-H gels contributing to bond strength are more, the flake and plank crystals with smaller contribution are less, which indicates that the destruction of cement agglomeration and water cluster provides a favourable environment for the formation of the C-S-H gels, it is favourable for needle-like, stick-like ettringite, and the granular and cluster C-S-H gels to generate, which can improve the microscopic structures and strength of recycled concrete.



(a) Ordinary forced mixing *(b) Vibration mixing*

Fig. 8 - 500 times SEM diagrams of recycled concrete aggregates

(a) Ordinary forced mixing *(b) Vibration mixing*

Fig. 9 - 6000 times SEM diagrams of recycled concrete aggregates

CONCLUSIONS

(1) The influence of vibration mixing on the behaviours of fresh recycled concrete is of great significance; the apparent densities of newly mixed recycled concrete tends to decrease with increasing the recycled aggregate contents; for the same percentage of recycled aggregates, the vibration mixing can improve the reduction phenomenon of apparent density; the vibration mixing can considerably reduce the slump loss of recycled concrete, and improve the mobility of recycled concrete; the vibration mixing can remarkably increase the air contents of recycled concrete and thus improve the durability of recycled concrete.

(2) Whether mixed by ordinary forced mixing or by vibration mixing, with the increase of the recycled aggregate contents, the compressive strengths tend to descend; for the same percentage of recycled aggregates, the compressive strength of recycled concrete mixed by vibration mixing is higher than that by ordinary forced mixing, which indicates that the vibration mixing can improve the mechanical behaviour of recycled concrete.

(3) By the utilization of ordinary forced mixing, the microscopic hydration reaction of recycled concrete specimens is not uniform, and the pore cracks are densely distributed; however, by the utilization of vibration mixing, the hydration of specimens surface is uniform without densely distributed pore cracks, and the structure of the microscopic interface is tight, followed by the formation of needle-like, stick-like ettringite, and the granular and cluster C-S-H gels, which shows that the hydration reaction by vibration mixing is more uniform and provide a favourable condition for C-S-H gels to form and can furthermore improve the microscopic structure and strength of recycled concrete.

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