Technical report

Pilot Study on Vibrated Rock-filled Concrete

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Abstract

This exploratory study investigated a new type of rock-filled concrete (RFC) named vibrated rock-filled concrete (VRFC). Different from the self-compacting concrete (SCC) used in traditional type of RFC, VRFC was built with ordinary pumping concrete (OPC) with the help of external vibration. The application of OPC further reduced the cement dosage and hydration heat of RFC, making it more widely applicable and environment-friendly without cost increase. It was proved that the fluidity of OPC could be significantly improved by external vibration, and the relationship between the flowing process and the mix proportion of OPC was also analyzed in the laboratory experiment. After verifying the feasibility of filling the rock voids with OPC in the laboratory, more than 700 m³ VRFC was constructed in the on-site experiment with roller compactors as the vibration source. Panoramic borehole color TV system and ultrasonic testing method were used to evaluate the quality of VRFC, and the influences of different parameters on the compactness as well as mechanical performance of VRFC were also analyzed.

1. Introduction

Almost since the invention of modern concrete technology, attempts have been made to increase concrete fluidity by applying external vibration. Records of imparting vibratory motion to fresh concrete can be traced back to as early as the 1930s. After the middle of the 20th century, many researches were carried out about the effects of different vibration methods, such as internal vibration (Ersoy 1962; Taylor 1976), surface vibration (Cannon 1972), form vibration (Forssblad 1971) and table vibration (Darvies 1951).

In recent years, it was found that the fluidity of concrete is proportional to peak vibrational velocity up to a critical level, which is proportional to the yield value of the unvibrated concrete, and peak fluidity is inversely proportional to the plastic viscosity of the unvibrated concrete (Banfill et al. 1999). The radius of action of the vibration source increases with vibrational velocity and plastic viscosity, and decreases with yield stress (Banfill et al. 2011). In terms of stability, it was reported that concrete stability under vibration could be enhanced by smaller density difference between coarse aggregates and mortar matrix (Chia et al. 2005). For self-compacting concrete (SCC), it had been confirmed that vibration could still be applied on it, without causing segregation in most cases, though the viscosity of the mixture should be given priority consideration (Safawi et al. 2005). In terms of mechanical properties, it was reported that concrete compressive strength almost increases linearly with the peak acceleration of vibration during casting when the peak acceleration is within a certain range (Kolek 1963). Within several hours after casting, a few minutes or even hours of continuous vibration did not significantly affect the concrete strength (Dunham et al. 2007; Tawfiq et al. 2010; Hong and Park 2015). For SCC, it was found that vibration in the mixing or casting stage has no significant impact on its dynamic modulus of elasticity, while the strength of SCC could be enhanced by vibration in the casting stage and be reduced dramatically by vibration in the mixing stage (Juradin et al. 2014).

In general, external vibration was used to enhance concrete fluidity as well as compactness, or was treated as an unavoidable external condition that may cause problems during concrete construction or curing. However, no attempt is found to use external vibration to enhance the ability of concrete to fill the rockfill voids.

Rock-filled concrete (RFC) is an innovative mass concrete technology first developed in 2003. During RFC construction, big rocks (D > 300 mm) are stacked to fill the surrounding steel formworks before they are cemented by SCC (Jin et al. 2005; An et al. 2009). Compared with conventional mass concrete technology, RFC is low-carbon, low-cost, easy-to-build, and can make better use of local materials (An et al. 2014; Xie et
Since the construction of the first RFC dam in 2005, more than 1 million cubic meters of RFC has been successfully applied in more than eighty projects all over the world (Wang et al. 2016). However, Xie (Xie et al. 2014) and Wang (Wang et al. 2018) proved that the compaction of traditional RFC is greatly affected by the performance of SCC. But the performance of SCC can vary significantly in the construction site due to wrong mix proportion, unstable material properties, transport delay, or poor adaptability of the admixture. Therefore, the application range of RFC may be broadened if the standard for SCC quality control is lowered after introducing some auxiliary engineering methods. Also, there are still great needs to further reduce the hydration heat and lower the unit price of RFC, in order to eliminate the cooling pipe as well as transverse joints in traditional RFC dams for concrete cracking prevention.

Nowadays, it is an overall trend for civil engineering industry to use materials with less hydration heat for mass concrete construction. However, there is almost no research in the field of filling the voids between big rocks with low-heat concrete (compared with SCC) under vibration. In this study, the authors attempt to fill the voids of the rockfill with ordinary pumping concrete (OPC) under external vibration, in order to make some improvements on traditional RFC. Compared with SCC, additional coarse aggregates and water take the place of fine aggregates and cementitious materials in OPC. Heat production is thus reduced, which further simplifies the cooling process and accelerates the construction speed of RFC. The lower cement dosage in OPC limits its fluidity, but under external vibration, OPC tends to have good fluidity and can even fill the rockfill without segregation. The new type of RFC built with OPC is named vibrated rock-filled concrete (VRFC).

This study first investigated the effects of vibration on the fluidity and filling ability of OPC in the laboratory. Then an on-site experiment was carried out, and the quality of VRFC built with OPC was evaluated and analyzed with different methods.

2. Laboratory experiment on the fluidity and filling ability of OPC under external vibration

2.1 Materials in the laboratory experiment
In the laboratory experiment, PO 42.5 cement produced by Beijing Jinyu Group Co., Ltd. and Grade I fly ash (Chinese Standards GB/T 1596-2017 2018) produced by Beijing Leiniuding Trade Co., Ltd. were used as the binding materials for OPC mixtures. Continuously grained crushed granites with the particle sieve size between 4.75 mm and 19 mm, which were produced in the quarry in Zhuozhou, Hebei province, were used as coarse aggregate, similar with common SCC. Type R210 Polycarboxylate-based superplasticizer (SP) produced by Beijing Sinoconfix Co., Ltd. was added into the mixing water of OPC.

2.2 OPC slump flow test under external vibration
The proportions as well as fluidity indicators of OPC are shown in Fig. 1. The water binder ratio (by volume) was first fixed to 1.1 to study the influence of SP dosage (as shown in test No. 1 - No. 5 in Table 1). Then the influence of water binder ratio (by volume) was studied (as shown in test No. 3 and No. 6 - No. 8 in Table 1), when the mass ratio of superplasticizer to cementitious materials was fixed to 0.80%.

In the experiment, the flowing processes of OPC spread were measured in the slump-flow test with and without vibration, respectively. The slump-flow test without vibration was carried out in accordance with relevant ASTM standard (ASTM C1611/C1611M-14 2014). For the slump-flow test with vibration, a plate vibrator (frequency = 48 Hz, amplitude = 4.5 mm) was used as the vibration source, and at the center of its upper surface fixed a steel plate. The flowing process of OPC spread during the experiment was recorded with a camera, making it possible to obtain the diameter of OPC spread in the flowing process by post analysis. The slump cone filled with OPC was placed in the center of the steel plate and was lifted immediately when the vibrator was activated.
set in motion, as shown in Fig. 1.

The flowing processes of OPC spread with and without vibration are shown in Figs. 2 and 3. It is clear that the fluidity of OPC is significantly improved by external vibration. One way to explain this phenomenon is to treat the OPC under vibration no longer as Bingham fluid but as granular system, just like the experiment recently put forward by Koch (Koch et al. 2019), which is consistent with the granular constitutive model of Hanotin (Hanotin et al. 2015). According to this model, the granular system has Bingham-like behavior when it is not under vibration, and has quasi-Newtonian behavior at low shear rates during vibration. Vibration disrupts the force chains by separating the grains in a process akin to adding thermal energy to a Brownian system (Anna et al. 2003). Similar conclusions were also drawn by some earlier researches (Tattersall and Baker 1988, 1989). Also, it is obvious that the smaller the fluidity of OPC mixtures is in the absence of external vibration, the more significant the increase in the fluidity by external vibration will be. For example, for OPC mixtures with the slump flow value of 200 mm – 300 mm under non-vibration condition, the diameter of the OPC spread could reach 500 mm – 700 mm after 10 s of external vibration, that is, the diameter of the spread is increased by 1 - 2 times. But for OPC mixtures with the slump flow value of about 600 mm under non-vibration condition, the effect of external vibration on increasing the diameter of the spread is obviously less pronounced.

The influence of SP dosage and W/B (by volume) on the flowing processes of OPC spread are also shown in Figs. 2 and 3, respectively. It is obvious that for a specified vibration time, the diameter of OPC spread with more SP dosage or higher W/B value (by volume) is larger. It can even be observed that there are still sig-

| Test No. | W/B (by volume) | C (kg) | F (kg) | S (kg) | G (kg) | W (kg) | SP (%) | Slump (mm) | SF (mm) |
|----------|----------------|-------|-------|-------|-------|-------|-------|-----------|--------|
| 1        | 1.1            | 169   | 306   | 844   | 770   | 197   | 0.60  | 20        | 200    |
| 2        | 1.1            | 169   | 306   | 844   | 770   | 197   | 0.70  | 125       | 230    |
| 3        | 1.1            | 169   | 306   | 844   | 770   | 197   | 0.80  | 180       | 315    |
| 4        | 1.1            | 169   | 306   | 844   | 770   | 197   | 0.90  | 255       | 660    |
| 5        | 1.1            | 169   | 306   | 844   | 770   | 197   | 1.00  | 265       | 700    |
| 6        | 1.0            | 178   | 321   | 844   | 770   | 188   | 0.80  | 165       | 270    |
| 7        | 0.9            | 187   | 338   | 844   | 770   | 178   | 0.80  | 0         | 200    |
| 8        | 0.8            | 198   | 357   | 844   | 770   | 166   | 0.80  | 0         | 200    |

Note: W/B - Water binder ratio by volume, C - Cement, F - Fly ash, S - Sand, G - Gravel, W - Water, SP - Mass ratio of superplasticizer to cementitious materials, SF – Slump flow.
significant differences between the flowing processes under external vibration for the two groups in which the W/B (by volume) are respectively 0.8 and 0.9, although the slump flow values of these two groups are both 200 mm under non-vibration condition (i.e., slump = 0 mm). However, from Figs 2 and 3, it appears that the SP dosage as well as W/B value (by volume) still has limits on accelerating the flowing processes of OPC spread under external vibration, indicating that the so-called saturation SP dosage still exists under these circumstances. The saturation SP dosage means that fluidity of cementitious material will not or just change slightly beyond this dosage (Flatt and Schober 2012).

Generally speaking, the most important index for SCC is that its slump flow value can exceed to about 600 mm without segregation (Okamura and Ouchi 2003; Chinese Standard JGJ/T 283-2012 2012), which supports the filling ability of SCC during RFC construction. In this experiment, the slump flow value of OPC could easily reach 700 mm within 20 s’ vibration without obvious segregation (shown in Fig. 4), which made it possible for us to do some research on the filling ability of OPC.

2.3 OPC filling test under external vibration
As shown in Fig. 5, a 400 mm × 400 mm × 600 mm mold, with the upper surface open, was made for the test. The mold was made of stainless steel sheet except that one side surface was made of polymethyl methacrylate, facilitating observation during the experiment. 64 L saturated surface-dry rubbles (bulk volume, the upper surface of the rubbles was equal to the marking line and the rubbles were recycled during the experiment) with an equivalent diameter of about 100 mm – 150 mm were placed in the molds, similar with the rockfill stacked on RFC construction site. The total mass of the rubbles in the test was 83.43 kg, while the saturated surface-dry...
density (SSD) of the rubbles was 2.75 g/cm³ (measured by drainage method). Thus, the void fraction of the rockfill was about 52.6%, which was in the normal range, considering the small size of the mold.

During the filling test, the mold filled with rubbles was vibrated by plate vibrator, while pouring OPC into the mold until no more OPC could enter the rockfill (observed by visual inspection). Define the total void volume in the rockfill before casting as \( V_0 \), and the volume of casted OPC at the end of the test as \( V_g \). Define the void filling ratio \( K \) as \( V_g / V_0 \). The \( K \), mix proportions as well as fluidity indicators of OPC for different tests (one test for each mix proportion) are shown in Table 2. The mix proportions of all the OPC used in the filling test were those that had been used in the previous slump-flow test under external vibration. The values of \( K \) for all the groups were around 70%. It is obvious that OPC has a certain filling effect on the rockfill under vibration in the laboratory experiment, though the filling effect is not entirely satisfactory. In actual engineering projects, the particle size of the rockfill is larger, resulting in larger voids between the particles, which can improve the filling property of SCC in the construction of traditional type of RFC (Xie et al. 2014; Zhang et al. 2016). Therefore, it is necessary to carry out on-site filling test for further exploration, and the hypothesis, which is about the effect of the relative size of the coarse aggregate in OPC and the rockfill granules on the compactness of VRFC, will be proved therein.

### 3. On-site experiment of VRFC

#### 3.1 Materials in the on-site experiment

In the on-site experiment, PO 42.5 cement produced by Jiaxing South Cement Co., Ltd. and Grade III fly ash (Chinese Standard GB/T 1596-2017 2018) produced by Ningbo Yunlu Building Materials Co., Ltd. were used as the binding materials for OPC mixtures. Continuously grained granites coarse aggregates produced by Yuyao Motong Quarry, with the particle sieve size between 1.25 mm and 16 mm, were used as coarse aggregate. Type R216 Polycarboxylate-based superplasticizer produced by Beijing Sinoconfix Co., Ltd., with the ability to maintain OPC fluidity during transportation, was added into the mixing water of OPC.

#### 3.2 Experiment procedure

The on-site experiment was carried out by the Hangzhou Bay in China, as part of a practical engineering project. As shown in Figs. 6(a) - 6(c), the casting process of VRFC consists of three steps: (1) The foundation pits, with a depth of about 1.0 m, were firstly dug out by excavators for casting, and were evenly heaped with rocks. (2) Then about 500 mm-thick OPC was tiled on these rocks by concrete pump trucks. (3) Finally, a roller compactor was driven back and forth three times on the covering OPC layer, with a speed of about 1.50 km/h. The motion track of the compactor’s geometric center in each cycle, named Z-shaped trace, is shown in Fig. 6(d).

As a result of the vibration, the OPC originally deposited on the surface of the rocks flowed through the voids of the rockfill, and bonded the rocks into dense VRFC. The
bubbling from the surface of VRFC under external vibration proved that VRFC became denser with the help of external vibration. The surface of VRFC after vibration is shown in Fig. 7.

In total, about 700 m$^3$ VRFC was constructed during the five batches of the experiment (about 100 m$^3$ – 200 m$^3$ in each batch), and effects of different factors on the quality of VRFC were examined respectively. The mix proportions, fluidity indicators as well as the 28-day uniaxial compressive strength (average value of three 150 mm × 150 mm × 150 mm cubic specimens) of OPC in each batch of the experiment are shown in Table 3.

Since the raw materials for OPC in the on-site experiment are different from those in the laboratory experiment, we redesigned the mix proportion based on the material properties of the on-site experiment, according to Chinese design handbook for concrete mix proportion (Chinese Standard JGJ 55-2011 2011). While redesigning, we still focused on the core issues of our research, that is, reducing cementitious materials dosage by increasing aggregates.

Other experimental factors in each batch of the on-site experiment are shown in Table 4. It should be pointed out that a tandem roller compactor (mess = 12600 kg, frequency = 60 Hz, vibratory force = 130 kN) and a single roller compactor (mess = 16000 kg, frequency = 28 Hz, vibratory force = 300 kN) were respectively used as the vibration source.

### 3.3 Compactness evaluation

(1) Panoramic borehole color TV system test

A panoramic borehole color TV system was used to take photos in the boreholes drilled vertically on the surface of VRFC, most of which with a depth of about 1 m into the VRFC for quality check. The borehole location is shown in Fig. 8. Based on these photos, the compactness of the VRFC in each batch is analyzed. The void selection process in the photos is illustrated in Fig. 9. The

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**Table 3 Mix proportions, fluidity indicators and 28-day compressive strength of OPC in the on-site experiment.**

| Batch No. | C (kg) | F (kg) | S (kg) | G (kg) | W (kg) | SP (kg) | Slump (mm) | 28-day compressive strength (MPa) |
|-----------|--------|--------|--------|--------|--------|---------|------------|----------------------------------|
| 1         | 159    | 237    | 775    | 917    | 189    | 10.50   | 175        | 25.8                             |
| 2         | 207    | 180    | 792    | 855    | 214    | 6.90    | 175        | 34.7                             |
| 3         | 207    | 180    | 792    | 855    | 214    | 7.35    | 175        | 32.6                             |
| 4         | 159    | 237    | 775    | 917    | 189    | 10.50   | 170        | 28.2                             |
| 5         | 159    | 237    | 775    | 917    | 189    | 10.50   | 170        | 28.2                             |

**Table 4 Other factors in each batch of the on-site experiment.**

| Batch No. | Roller compactor | Particle size range of the rockfill (mm) | Particle sieve size range of OPC coarse aggregate (mm) |
|-----------|------------------|------------------------------------------|-------------------------------------------------------|
| 1         | tandem roller compactor | 200-600                                  | 2.36-26.50                                             |
| 2         | tandem roller compactor | 150-400                                  | 2.36-16.00                                             |
| 3         | tandem roller compactor | 150-400                                  | 2.36-16.00                                             |
| 4         | single roller compactor | 150-400                                  | 2.36-16.00                                             |
| 5         | single roller compactor | 200-600                                  | 2.36-16.00                                             |

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Fig. 6 Schematic of casting OPC under vibration. (a) fill the casting area with rocks. (b) tile OPC on the rocks. (c)vibrate OPC with roller compactor. (d) The motion track of the compactor’s geometric center.

**Note:** In Fig. 6(d), distance between the start/end point and the adjacent vertical boundary, a, is half the length of the compactor. Distance between two adjacent horizontal lines, b, is half the width of the compactor.
voids on the surface of the boreholes were circled with dashed lines by the quick selection tool of Adobe Photoshop software, according to visual inspection. Considering that the dashed lines are quite blurred, solid red lines were supplementarily drawn outside the dashed lines in Fig. 9, for the convenience of the readers. For each photo, the total pixel number of the selected parts was calculated and was defined as \( N(\text{void}) \). The total pixel number in each photo is defined as \( N(\text{total}) \). Subsequently, \( N(\text{void})/N(\text{total}) \) was defined as the defect rate of the analyzed photo. Judging from the photos of the core samples, the defects (cavities with a diameter of about 30 mm – 50 mm appear occasionally) were mainly caused by the failure of OPC to flow into the occluded parts of the rockfill (e.g. directly under the large stone) even with the help of external vibration, which can also be illustrated in Fig. 9.

The defect rate values are shown in Table 5. The indicator for quality evaluation is the average defect rate of each batch. Those significantly larger defect rate values in each batch are included in the calculation of the average value of each batch, since as mentioned above, the distribution of the defects is quite concentrated in VRFC (e.g. directly under the large stone). That is to say, it is not possible to truly reflect the quality of VRFC by counting only those photos with a smaller defect rate in each batch, since the defect rate of a particular photo may still be quite small even if there are obvious defects in other parts of VRFC. Following conclusions can be drawn after comparing the results of different batches:

1. Smaller coarse aggregate size in OPC reduces the defect rate of VRFC. The roller vibrator used in the first and the second batch were identical. And in the first batch, the fluidity of OPC was better and the particle size of the rockfill was larger, which both...
reduced the defect rate of VRFC (we will prove it in following paragraphs). However, the average defect rate of the first batch is much higher, which is obviously caused by the difference in the particle size of the coarse aggregates in OPC.

2. Better fluidity of OPC reduces the defect rate of VRFC. The defect rate in the second batch is higher than that in the third batch, and the only difference between the second and the third batch is that the OPC in the third batch had better fluidity.

3. Stronger vibration intensity does not significantly reduce the defect rate of VRFC in our on-site experiment, since there is no much difference between the average defect rate in the third and the forth batch. Stronger vibration intensity in the fourth batch was the main difference between the third and the fourth batch (the fluidity of OPC, the coarse aggregate size of OPC as well as the particle size of the rockfill in the third and the fourth batch were relatively similar).

4. Larger particle size of the rockfill reduces the defect rate of VRFC. The average defect rate in the fourth batch is higher than that in the fifth batch, and the only difference between the fourth and the fifth batch is that the particle size of the rockfill in the fifth batch was larger. Similar conclusion was also drawn by earlier work about traditional type of RFC, since larger particle size of the rockfill will result in larger voids between the rock particles, which will reduce the particle jamming phenomenon of concrete when it flows through the rockfill voids (Zhang et al. 2016).

For two recent traditional RFC projects built with SCC, the defect rates are respectively 0.16% and 0.81%, with good compactness uniformity (Chinese Standard NB/T 1077-2018 2019). In our on-site VRFC experiment, only by proper control of coarse aggregate size in OPC, fluidity of OPC as well as particle size range of the rockfill can the average defect rate reduce to 0.45% in the fifth batch, which can be regarded as a satisfying level. Otherwise, the average defect rate can reach 3.70% in the first batch, and also with poor compactness uniformity. Therefore, in terms of compactness, OPC in VFRC is still not acceptable to replace SCC in traditional type of RFC.

(2) Ultrasonic test
Ultrasonic testing method was also applied to evaluate the quality of VRFC, and the test results are shown in Table 6. A pair of ultrasonic probes (a transmitter probe and a receiving probe) were first inserted into borehole No. 1-4 and No. 1-5, respectively. The ultrasonic wave speed at different depths in the VRFC between these two boreholes was measured for three times (Test 1, Test 2 and Test 3 in Table 6). Next, the ultrasonic wave speed between borehole No. 1-4 and No. 1-6 (Test 4 in Table 6)
and the ultrasonic wave speed between borehole No. 1-5 and No. 1-6 (Test 5 in Table 6) were also measured.

Overall, most of the measured wave speeds are between 3.5 km/s and 4.0 km/s. In comparison with the previous detection results of RFC by the same means (often between 3.5 km/s and 5.0 km/s) (Chinese Standard NB/T 1077-2018 2019), it is believed that the test results in our experiment confirm the acceptable compactness of VRFC, considering that the ultrasonic test was carried out in the batch with the worst compactness (the first batch). The results in Test 1, Test 2, and Test 3, which were carried out between the same two measurement boreholes, are close with each other, indicating that the test method is reliable. For three locations with lower wave speeds (Test 4, depth = 800 mm; Test 5, depth = 800 mm; Test 5, depth = 600 mm), the panoramic photos show that VRFC at these depths do have obvious defects, as shown in Fig. 10.

### 3.4 Mechanical properties evaluation

Among all the core samples taken from the boreholes, samples with a rock-OPC interface which crosses the whole sample are our focuses, though there are not many samples of this type. The uniaxial compressive strength of these core samples was tested and analyzed, in order to evaluate the mechanical performance of VRFC. The strength as well as the depth of sample midpoint are shown in Table 7. The strength is uniformly converted to the 28-day strength, after the samples’ diameter and height are both converted to 100 mm. It should be

| Depth (mm) | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 |
|-----------|--------|--------|--------|--------|--------|
| 0 mm      | 3.654 km/s | 3.595 km/s | 3.745 km/s | 3.743 km/s | Data corrupted |
| 200 mm    | 3.745 km/s | 3.634 km/s | 3.919 km/s | 3.826 km/s | 3.147 km/s |
| 400 mm    | 3.567 km/s | 3.664 km/s | Data corrupted | 3.647 km/s | 3.739 km/s |
| 600 mm    | 3.605 km/s | 3.673 km/s | 3.595 km/s | 3.466 km/s | 2.701 km/s |
| 800 mm    | Data corrupted | Data corrupted | Data corrupted | 2.636 km/s | 2.526 km/s |

**Note:** Test 1, Test 2 and Test 3 measured the ultrasonic wave speed between borehole No. 1-4 and No. 1-5 repetitively. And similarly, borehole No. 1-4 and No. 1-6 for Test 4, borehole No. 1-5 and No. 1-6 for Test 5.

| Borehole No. | Compressive strength (MPa) | Contact angle | Depth of sample’s midpoint (m) |
|--------------|---------------------------|---------------|-------------------------------|
| 1-5          | 17.6                      | 45°           | 0.2                           |
| 1-5          | 15.6                      | 60°           | 0.6                           |
| 1-6          | 17.7                      | 60°           | 0.7                           |
| 1-7          | 17.1                      | 60°           | 0.2                           |
| 2-3          | 16.0                      | 60°           | 0.3                           |
| 2-5          | 15.7                      | 45°           | 0.4                           |
| 3-6          | 15.0                      | 45°           | 0.6                           |
| 3-6          | 14.8                      | 45°           | 0.6                           |
| 4-2          | 16.7                      | 45°           | 0.8                           |

**Note:** The contact angles are the estimated values based on visual observation.

![Fig. 10 Panoramic photos for borehole No. 1-4, borehole No. 1-5, borehole No. 1-6.](image-url)
pointed out that sample from borehole No. 1-7 has obviously lower strength, and it is found that there is obvious suspected weak strip in the VRFC near the location of this sample (panoramic photo at the location of sample No. 1-7 is shown in Fig. 11). Typical failure process of these samples is shown in Fig. 12, and it can be seen that the failure does occur along the contact surface, which means the strength actually reflects the bonding strength between rock and OPC.

In general, the strength of the VRFC samples is around 15 MPa, which indicates that the strength level of VRFC can be judged as C10, which is sufficient for the non-critical part of structures such as low dams, dikes and cofferdams. The sample strength varies little among different batches, which illustrates that coarse aggregate size in OPC (by comparing borehole No. 1-5, No. 1-6, No. 1-7 and borehole No. 2-3, No. 2-5), fluidity of OPC (by comparing borehole No. 2-3, No. 2-5 and borehole No. 3-6), vibration intensity (by comparing borehole No. 3-6 and borehole No. 4-3), particle size of the rockfill (by comparing borehole No. 4-3 and borehole No. 5-2) does not affect the strength of the samples significantly. This may because larger coarse aggregate size, poorer fluidity and smaller particle size of the rockfill does result in a higher overall defect rate of VRFC, but most of the defects in VRFC, such as the aforementioned cavities caused by the failure of OPC to flow into the occluded parts of the rockfill, are quite concentrated. Concentrated cavities in VRFC structure cannot exist inside the core samples since the size of the core samples is not large enough, that is, the core sample will be broken if there is a cavity inside it. Thus, the differences in the defect rate of different batches don’t correspondingly result in significant difference in the strength of the samples.

The strength of the core samples obtained from VRFC is lower than the strength of OPC (previously shown in Table 3), and the strength of OPC has little effect on the strength of the core samples. These phenomena are different from traditional type of RFC. For traditional type of RFC, the strength of the core samples is always greater than the strength of the SCC (Huang et al. 2008; Chen et al. 2018, 2019; Chinese Standard NB/T 1077-2018 2019). And at the same time, the strength of SCC has a decisive effect on the bonding strength of the contact surface between rock and SCC, which in turn determines the strength of the core samples. In this research, considering that most sample failures occur along the contact surface, the lower strength of the samples may result from the weak compactness or the unsatisfying bonding strength between rock and OPC. In the former work of Wang (Wang et al. 2016), rockfill is filled by ordinary mortar with the help of external vibration, and the ITZ porosity on the rock-mortar interface increases obviously, when comparing with the control group in which the rockfill is fill by self-compacting mortar.

4. Conclusions

Following conclusions can be drawn after the experiments in the laboratory and engineering site:

1. External vibration can significantly improve the fluidity of OPC, and OPC with higher SP dosage or higher W/B still spreads faster under external vibration. For OPC with small fluidity under non-vibration conditions, the diameter of OPC spread may be increased by 1 - 2 times by 10 s of vibration, compared with the spread diameter without external vibration. By visual inspection, no evident segregation is found in the OPC spread used in our laboratory experiment after external vibration.

2. Under external vibration, 1m-thick rockfill can be densely filled with OPC, though some defects still
exist in the interior of VRFC. Parameters such as coarse aggregate size in OPC, fluidity of OPC, particle size range of the rockfill all influence VRFC compactness. Only with proper control of these parameters can the average defect rate of VRFC reduced to a satisfying level (0.45%).

3. In the compressive strength test, VRFC sample failures often occur along the rock-OPC interface. The strength of the core samples obtained from VRFC is lower than the strength of OPC, and OPC strength has little effect on the strength of the core samples, which are both different from traditional type of RFC. These phenomena may result from the weak compactness or the unsatisfying bonding strength between rock and OPC.

4. For rockfills, a relatively mature construction scheme for VRFC is established, in which a roller compactor vibrates the OPC-covered rockfill back and forth for three times in a Z-shaped trace, with a speed of about 1.50 km/h. Further study is still needed for the optimization of this construction scheme.

The low quality requirements for OPC during VRFC construction, which is mainly due to external vibration, expand the application range of RFC apparently. Compared with traditional RFC, the total price of the materials used in VRFC is cheaper, and the CO₂ emission is lower, as a result of the decreased cementitious materials dosage as well as the simplified construction method (e.g. the temperature control method). In summary, for future engineering projects, VRFC have certain meanings in structures such as low dams, dikes, and cofferdams, though more detailed studies are still needed.

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