ISSN 1027-5495. Functional Materials, 29, No.2 (2022), p. 268-273.
doi:https://doi.org/10.15407/fm29.02.268

Investigation of the effect of recycled concrete additives on the properties of cement-based materials

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Received February 22, 2022

In this paper, the aim is to explore the potential of recycled concrete powder (RCP) as an internal curing agent in reducing the shrinkage of cement-based material. Different amount of RCP was added into cement paste and the autogenous shrinkage of cement matrix was measured. Low-field nuclear magnetic resonance (NMR) was applied to monitor the water state during the hydration process. Scanning electronic microscope (SEM) was used to observe the micro-morphology of RCP added cement matrix. The results show that the autogenous shrinkage of samples with addition of RCP was remarkably reduced. This is because much water was captured by RCP and the water will be released to balance the capillary pressure of the cement matrix, thus leading to a smaller deformation. SEM images also showed that there were fewer microcracks after adding RCP. Although the shrinkage was inhibited by RCP to some extent, the compressive strength of samples with the addition of RCP decreased. Our work proves that RCP is an effective internal curing agent for cement-based material.
Keywords: internal curing agent, autogenous shrinkage, recycled concrete powder, low-field NMR.

Дослідження впливу добавок переробленого бетону на властивості матеріалів на основі цементу. *Xuefeng Yuan, Gang Liao*

Вивчено властивості переробленого бетонного порошку (RCP) як внутрішнього затверджувача для зменшення усадки матеріалу на основі цементу. Методом ядерного магнітного резонансу (ЯМР) проводився контроль стану води в процесі гідратації. Скануючий електронний мікроскоп (SEM) використовували для спостереження мікроморфологією цементної матриці з додаванням RCP. Результати показують, що аутогенне усадження зразків з додаванням RCP значно зменшується. Зображення SEM також показали, що після додавання RCP спостерігається менше мікротріщин. Хоча RCP пригнічу усадку, міцність на стиснення зразків з додаванням RCP знижується. Результати показують, що RCP є ефективним внутрішнім затверджувачем матеріалів на основі цементу.

1. Introduction

With the development of urbanization, massive concrete waste is produced in China, which not only causes severe environment pollution, but also occupies a large amount of land. At present, the fine fraction of concrete waste, recycled concrete powder (RCP), has not been disposed well [1–3]. Some RCP are simply sent to landfill, and other part of RCP are used as building materials of low value, such as supplementary cementitious materials (SCMs), fillers, and feedstocks for clinker [4–7]. The main reason for the low recycling rate of RCP is that RCP varies in chemical constitutes and physical properties. Adding excessive RCP to cement-based material can lead to the performance degradation of the cement matrix. For instance, the main product of RCP is hydrated cement paste with low hydration activity, and adding RCP into cement will degrade the mechanical property of the cement matrix [8–9]. Also, the surface of RCP is rough and the interface transition zone (ITZ) between RCP and the new cement paste is weak, which negatively affects the durability of concrete. Therefore, the conventional method is limited in promoting the reutilization of RCP, and people should provide some new insights into the recycling of RCP.

Nowadays, a high performance cement-based material (HPC) has been developed. However, the autogenous shrinkage of the cement paste is remarkable, which is a key factor influencing the performance of HPC. Some shrinkage reducing agents (SRA), such as, alcohol and polyoxyethylene, have been developed to reduce the shrinkage by decreasing the surface tension [10–12]. And some expanding agents like MgO and CaO are used to offset the deformation of concrete [13]. Recently, internal curing agents like superabsorbent polymer (SAP) are added to cement to reduce the autogenous shrinkage [14–15]. SAP has very high water absorption, and when SAP is introduced into cement, much water will be absorbed by SAP. With progressive cement hydration, free water in capillary pores is consumed fast, and water absorbed in SAP will migrate from SAP to cement to compensate the internal moisture of cement, thus reducing the shrinkage. Therefore, it can be deduced that the substance with high water absorption can be used as an internal curing agent to reduce the shrinkage of concrete. It should be noticed that RCP has rough surface as well as high water absorption. From this point of view, RCP can be employed as internal curing agents for reducing the shrinkage of concrete in theory.

The aim of this paper is to investigate the shrinkage reducing effect of RCP on the cement matrix. Specifically, various amounts of RCP were added to cement, and the autogenous shrinkage of the cement paste was measured. In addition, low field nuclear magnetic resonance (NMR) was applied to monitor the internal water state. Also, a scanning electronic microscope (SEM) was used to observe the microstructure of the cement matrix added with RCP. This work may provide a new application field for RCP and improve the recycling rate of RCP.

Table 1. Chemical compositions of cement and RCP

No.	CaO	SiO_2	Al_2O_3	MgO	SO_3	LOI
PC	59.89	24.06	6.34	0.98	2.46	2.07
RCP	31.03	47.49	11.71	2.04	0.914	1.06

PC is Portland cement.

Table 2. Mix proportions of RCP added cement paste

No.	Cement, g	RCP, g	Water, g
R-0	100	–	35
R-15	85	15	35
R-30	70	30	35

2. Experimental

2.1 Raw material

Cementitious material was P·O 42.5 cement, and recycled concrete powder (RCP) was provided by Shanghai Recycled Aggregate Factory. RCP were sieved through a standard sieve with 100 mesh. The chemical compositions of cement and RCP is listed in Table 1.

2.2 Sample preparation

Various amounts of RCP were added into cement, and the ratio of water to solid was fixed as 0.35. The mix proportions are shown in Table 2. Firstly, cement and RCP were mixed in a mortar mixer, and then water was added with continuous stirring. The fresh cement paste was poured into a bellow to measure shrinkage.

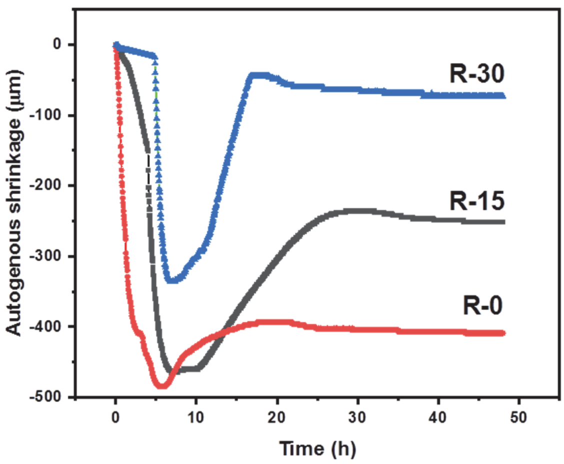

Fig. 1. Deformation of cement paste with different amount of RCP.

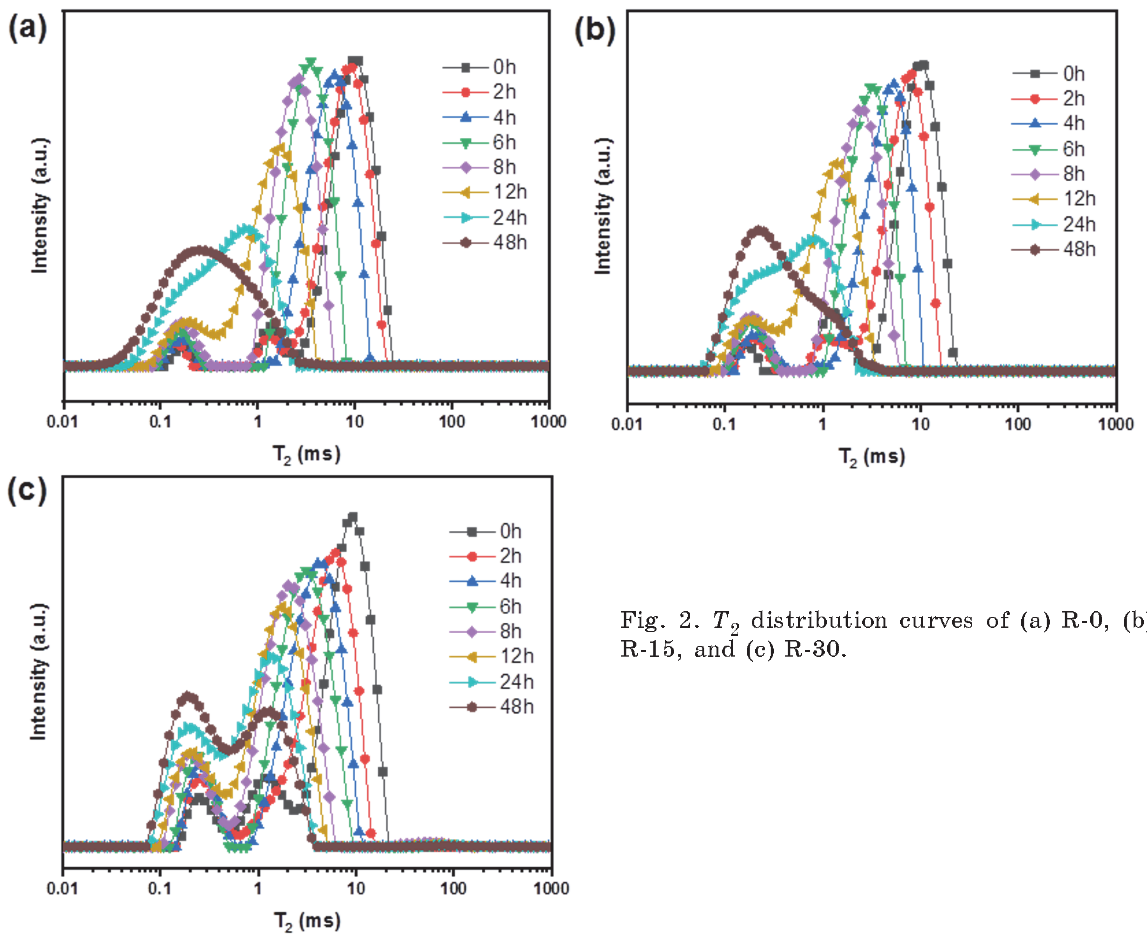

Fig. 2. T_2 distribution curves of (a) R-0, (b) R-15, and (c) R-30.

2.3 Characterization

2.3.1 Autogenous shrinkage measurement

The autogenous shrinkage was continuously measured for 48 h by an apparatus according to American standard ASTM C1698. The apparatus was made up of a bellows (Φ20×420 mm) and an electronic dial gauge. In a typical test procedure, the fresh cement paste was added to the bellows with vibration until the bellows was filled with cement paste. And then the bellows was placed horizontally. The deformation of the bellow was monitored by an electronic dial gauge.

2.3.2 Low-field NMR

A NMRC12-010-T type NMR Analyzer (Niumag Analytical Instrument Co., Ltd, China) was used in this work. The parameters of low-field NMR were described in our previous work [16]. 1H was the probe to characterize the state of water. Specifically, a Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence was used to measure the transverse relaxation time (T_2) of ^{1}H in free water. In different chemical environments, water has a different value of T_2; and T_2 can be regarded as an indicator of microstructure. Generally, a higher T_2 value corresponds to a larger pore size in the cement matrix.

3. Results and discussion

3.1 Autogenous shrinkage

Figure 1 displays the deformation of the cement matrix with different addition of RCP. It can be seen that the deformation of all samples increased with hydration time, indicating shrinkage occurred continuously in the hydration process. Especially, up to 8 h of hydration, the deformation was large, because autogenous shrinkage is more noticeable under lower water-to-cement ratio conditions. After 8 h, the deformation increased slightly. Although the autogenous shrinkage can?t be absolutely avoided during the hardening of cement paste, the deformation varied in different samples. With increasing addition of RCP, autogenous shrinkage was contained, since the deformation of R-30 was much lower than that of R-0 and R-15. This directly shows that RCP can reduce the autogenous shrinkage of cement paste. The shrinkage reducing effect

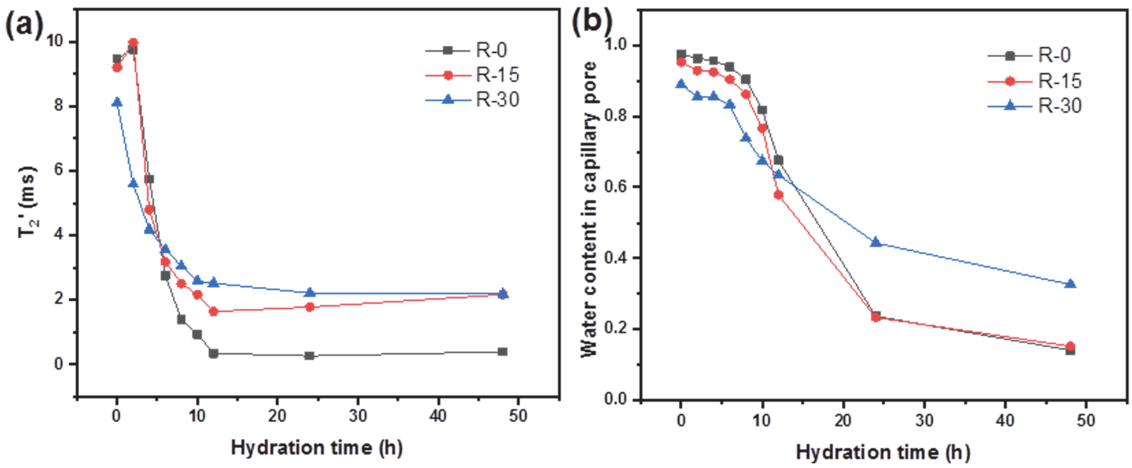

Fig. 3. (a) Plot of weighted average of T_2 in the range of 1 to 100 ms vs. time; (b) Plot of water proportion in capillary pores vs. time.

of RCP can be attributed to two aspects. On the one hand, RCP mainly consists of hydrated cement paste and quartz, which have high volume stability and chemical inertness. During the process of cement shrinkage, the development of microcracks can be inhibited by RCP. And with an increase in the rate of replacement of RCP, less cement paste is involved in the hydration reaction, which means that less microcracks will form. On the other hand, RCP has a high water absorption ability, which can play the role of internal curing agent. And this effect will be discussed in detail in the next part.

3.2 Low-field NMR

Figure 2 shows the time distribution ($T2$) of the transverse relaxation of the samples at different times of hydration. It is well known that the value of T_2 represents the relaxation state of ^1H in free water, which is determined by the confined state of water. Generally, water has higher relaxation degree in larger pores, which corresponds to higher T_2. Overall, T_2 in all samples presents a multimodal distribution, indicating that the porosity in cement paste is complicated. At the early hydration stage, the main peak of T_2 is located in the range of 1 to 100 ms, which corresponds to the water in capillary pores. This portion of water is important for autogenous shrinkage, and when the water in the capillary pores is consumed quickly, autogenous shrinkage becomes severe. As hydration progressed, the location of main peak shifted towards lower T_2; this can be easily explained by the fact that more gel pores were formed during the hydration process, and the size of the gel pores is usually smaller than the size of the capillary pores.

Although all the samples had the same trend, the proportion of capillary pore water was different. It was noted that after 24 hours R-0 and R-15 had little capillary water in the pores, but for R-30 the content of capillary water in the pores was still high. The main reason is that RCP has high porosity and water absorption, and most water was captured by RCP at the early stage. When the internal moisture of cement paste decreases due to hydration, the water absorbed by RCP will be released into the capillary pores to promote further hydration of cement; at the same time, autogenous shrinkage is suppressed due to less capillary pressure.

Figure 3a shows the weighted average of T_2 (T_2') in the range of 1 to 100 ms at different hydration times. It can be seen that T_2' of R-0 decreased with time, but T_2' of R-15 and R-30 first increased and then decreased with time. This can be explained by the fact that when RCP was added, it first absorbed water; since the RCP pore size was larger than the capillary pore size in the cement paste, the water was released and took part in the hydration reaction. In addition, R-30 had the largest T_2', and T_2' of R-15 was larger than that of R-0, which was proportional to the amount of RCP. It was mentioned before that in the range of 1 to 100 ms, T_2 is an indicator of water in capillary pore, so the peak area in the range of 1 to 100 can represent the content of capillary pore water. In Fig. 3b, the relative contents of capillary pore water are compared. It is obvious that the capillary pore water content decreased with time for all samples, and the capillary pore water content of R-30 was higher than that of R-0 and R-15. This demonstrated that water in

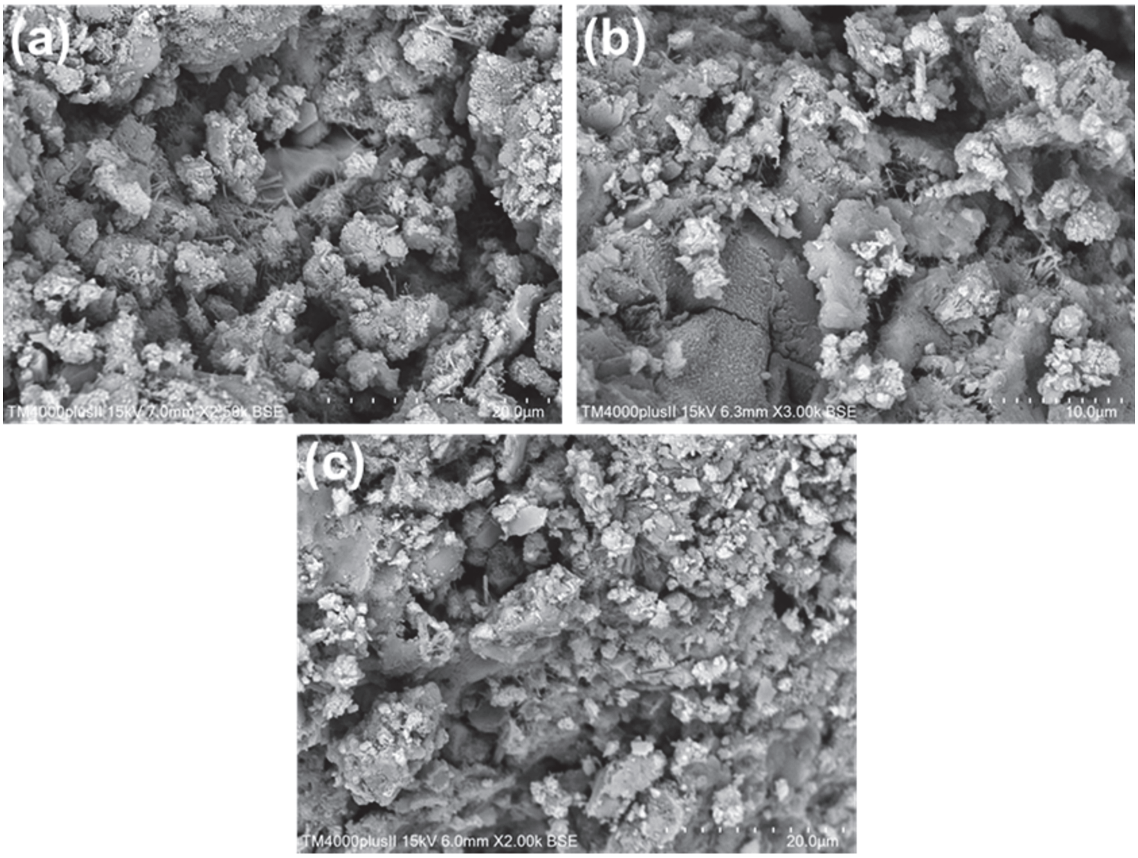

Fig. 4. SEM images of (a) R-0, (b) R-15, and (c) R-30.

RCP was slowly released to cement paste, thus maintaining a balance of internal capillary pressure, which contributed to reduce autogenous shrinkage.

3.3 Micro-morphology

Figure 4 shows the micro-morphology of all samples. It's clear that there were many microcracks in R-0 as shown in Fig. 4a, which were caused by the autogenous shrinkage. After adding RCP to cement paste, the number of microcracks was obviously reduced in R-15 (Fig. 4b) and R-30 (Fig. 4b). And the cement matrix of R-30 was most compacted. This confirmed the shrinkage reduction effect of the RCP in the cement matrix.

3.4 Compressive strength

Figure 5 displays the compressive strength of all samples. The compressive strength increased with hydration time, but decreased with the RCP content. This is due to low RCP activity; and less hydration products such as C–S–H gel and $Ca(OH)_2$ were produced in R-15 and R-30 compared to R-0. In other research, similar phenomenon was also observed. For instance, after introducing internal curing agents like SAP, the autogenous shrinkage was reduced, but the water-to-cement ratio was high, especially at the interface transition zone (ITZ), and more ettringite (AFt) was produced at ITZ with the formation of many micro-holes, as a result of which the compressive strength decreased.

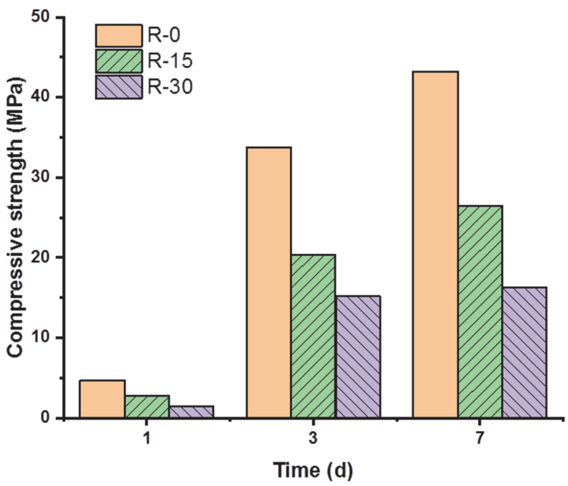

Fig. 5. Compressive strength of all samples.

4, Conclusions

In summary, RCP has been successfully utilized as an internal curing agent to reduce the autogenous shrinkage of cement-based material. The results show that the deformation of the cement matrix deceased with the addition of RCP. This effect can be attributed to two reasons. On the one hand, RCP is relatively inert and can inhibit the development of cracks. On the other hand, much water was absorbed on RCP and the water will be released slowly during the hydration process, keeping the balance of capillary pressure in the cement matrix, thus reducing the autogenous shrinkage. The SEM images also show that less microcracks were observed in the cement matrix added with RCP. In the cement matrix with the addition of RCP, the compressive strength decreased, but still remained at a relatively high level, which had little effect on the characteristics of the cement.

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