Compressive Strength Development of Dune Sand Reactive Powder Concrete (RPC) Under Different Curing Conditions

S Ahmed¹, F Abed² and M A Mannan³

¹ Sara Ahmed, Graduate Student, American University of Sharjah, UAE, g00049654@aus.edu
² Farid Abed, Professor at American University of Sharjah, UAE, fabed@aus.edu
³ Mohamed Abdul Mannan, Professor at Universiti Malaysia Sarawak, Malaysia, mannan@unimas.my

Corresponding author email fabed@aus.edu

Abstract. Reactive powder concrete (RPC) is a special type of concrete with remarkable properties, particularly compressive strength. Some of its main disadvantages include its high cement and SF content, fine quartz with a preferred size of 150 µm - 600 µm, and low water-to-binder ratio. These characteristics increase the cost of RPC production and affect sustainable development. Because of this, researchers have resorted to exploring substitutes to cement and quartz to produce an eco-friendlier type of RPC. Accordingly, this research aims to study the compressive strength development of RPC prepared with dune sand and supplementary cementitious materials (SCM). Three main factors were investigated including 1) replacing cement with 30% ground granulated blast furnace slag (GGBS), 2) using ternary blends of GGBS and fly ash (FA) in RPC, and 3) applying 100°C hot air curing (HAC) to RPC. Overall, the results showed that the compressive strength of HAC and water cured specimens exceeded 120 MPa after 12 hours and 28 days, respectively. Moreover, the compressive strength development of the mixes incorporating SCM was slower than that of the control mix incorporating cement only under HAC conditions.

1. Introduction
Reactive powder concrete (RPC) is considered an innovative type of ultra-high-performance concrete (UHPC) that was developed in the '90s [1]. RPC exhibits superior properties and microstructural properties as compared to ordinary concrete. Some of its properties as reported in the literature include compressive strength, modulus of rupture, and fracture energy which are typically in the ranges of 200-800 MPa, 25-150 MPa, and 12-40 kJ/m², respectively [2], [3]. Such properties make the use of RPC desirable in slender elements, tall buildings, large-span structures [2]. The properties of RPC are usually attained through microstructural engineering approaches which include 1) the replacement of coarse aggregates with fine aggregates (typically quartz) with sizes of 150 µm and 600 µm, 2) the use of high cement and silica-rich components with typical amounts of 800–1100 kg/m³ and 150–300 kg/m³ of cement and silica fume (SF), respectively, 3) reduction of the water-to-binder (w/b) ratio and 4) the incorporation of steel fibers [4].

Although such approaches produce RPC with remarkable properties, there are several disadvantages linked to RPC and its production. For example, the use of quartz which is preferable in RPC is limited due to the quartz scarcity in some countries. Also, the population growth has resulted in a boost in the construction industry worldwide. This has increased the production and use of cement which contributes to around 8 to 10% of the total anthropogenic greenhouse gas (GHG) emissions [5]. The global production of cement in 2019 was estimated to be around 4.1 billion tons and is expected to increase by 216% by 2030 [6]. Therefore, since RPC comprises high cement content as compared to
ordinary concrete, it is crucial to explore other sustainable alternatives to cement. Moreover, the combined use of fine aggregates in addition to the high amounts of cement and SF increase the heat of hydration and make RPC vulnerable to shrinkage. Due to these challenges, many studies have explored the use of supplementary cementitious materials (SCM) and other environmentally friendly materials to produce RPC with similar properties to that of the conventional RPC.

The use of SCM in concrete is not only desired from an environmental perspective but also to enhance properties such as workability, pumpability, bleeding, and longevity of concrete, which influence associated emissions over a structure's lifetime [7], [8], [9]. Hasan et al. [10] replaced 50% of cement with combinations of fly ash (FA) and metakaolin. A reduction in compressive strength of around 43 and 38% was observed as compared to the control mixture. However, the strength did not exceed 60 MPa and thus cannot be classified under the UHPC category. Liu et al. [11] replaced up to 50% of cement with FA and ground granulated blast furnace slag (GGBS). The result showed that the compressive strength of all specimens decreased with the use of SCM; yet achieved strengths that are higher than 110 MPa at 28 days of standard curing conditions. Note that in this study SCM was used with superabsorbent polymers (SAP) to reduce the shrinkage effects of concrete and the study concluded that the use of high amounts of GGBS is feasible when used with SAP.

The use of ternary blends has also been investigated in the production of RPC [12], [13]. The use of ternary blends, in general, is desirable in concrete as it may reduce the concrete production costs, may lower the embodied energy, and also may reduce the carbon footprint [14]. In [12] and [15] both studies showed that using ternary blends of SF-GGBS-FA performs better as compared to binary blends. However, it should be noted that ternary blends do not always necessarily exhibit enhanced strength as compared to binary blends as will be shown in the current study. In addition to the aforementioned challenges of RPC, other challenges also include complex curing regimes and a lack of knowledge and guidelines of mixing procedures. Therefore, there is a need to facilitate the production and application of such concrete at low costs. Over the past decades, there has been a growing interest in studying the impact of autoclaving and steam curing on the properties of RPC. For instance, it is known that the optimal time for RPC to achieve its highest strength can vary mostly from 8 to 10 hours under autoclaving [2]. However, little literature is available on the optimal time and effect of hot air curing (HAC) as compared to autoclaving and steam curing. 

On this basis, this research aims to study the impact of hot air curing on RPC with ultra-high-strength (>120 MPa) developed using locally available construction materials in the UAE. Dune and crushed sand which is the commonly used types of fine aggregates in the UAE will be used in place of quartz with larger aggregate sizes of 150 µm–1.18 mm than those used in the conventional RPC. The cement content will be reduced by 30% using GGBS and FA to minimize the carbon footprint and the effect of ternary blends will be compared to binary blends (SF-GGBS-FA vs. SF-GGBS). Since the compressive strength is the main property that characterizes RPC, this paper will mainly be focused on the compressive strength development of RPC up to 90 days. Two curing regimes will be implemented and evaluated including 1) water curing (WC) and 2) hot air curing (HAC).

2. Experimental Program
In this section the materials used, mix proportions, sample preparation, and test conducted will be presented.

2.1. Materials and mix proportions
All mixes incorporated ordinary Portland cement and silica fume (SF) with specific gravities of 3.14 and 2.2, respectively. A polycarboxylate-based high-range water-reducing admixture that is commercially available was used in all mixes. The cement used had a Blaine fineness of 318 m²/kg while the ground granulated blast furnace slag (GGBS) and fly ash (FA) had a Blaine fineness of 417 m²/kg and 474.3 m²/kg, respectively. The fine aggregates used (shown in figure 1) included dune sand (desert sand) and crushed sand which are the commonly used types of fine aggregates in the UAE. The crushed sand was sieved to have particle sizes ranging from 150 µm to 1.18 mm. Brass-coated fibers with an aspect ratio of 87 were used in all mixes (13 mm length & 0.16 mm diameter). The tensile strength of the used fibers was 3000 MPa.
Since RPC comprises high amounts of cement and SF which reaches up to 1100 kg/m³ and 300 kg/m³, respectively, the cement content in this study was reduced by 30% to 571 kg/m³. To achieve the objectives of the study three main mixes were developed for the compressive strength evaluation as shown in table 1. The three mixes included: 1) a control mix with cement only (CM), 2) a 30% GGBS mix (G30), and 3) a ternary blend mix with 15% GGBS and 15% FA (G15F15). The references of the mix are given as shown in table 1.

### Table 1. Mix designs.

|                  | CM  | G30 | G15F15 |
|------------------|-----|-----|--------|
| Cement (kg/m³)   | 818 | 571 | 571    |
| SF (kg/m³)       | 272 | 272 | 272    |
| GGBS (kg/m³)     | -   | 222 | 122    |
| FA (kg/m³)       | -   | -   | 122    |
| Crushed sand (kg/m³) | 633 | 633 | 633    |
| Dune sand (kg/m³) | 458 | 458 | 458    |
| Water (kg/m³)    | 185 | 185 | 185    |
| Steel fibers (kg/m³) | 141 | 141 | 141    |
| Water-to-binder ratio | 0.17 | 0.17 | 0.17   |
| Aggregate-to-binder ratio | 1.0  | 1.0  | 1.0    |

2.2. Mixing procedure, sample preparation, and curing regime

A Hobart mixer was used to produce all the RPC mixes of the study. The mixing procedure adopted included a four-stage mixing which was used in a study conducted by Hiremath and Yaraga [16]. The mixing procedure included four main stages. In the first stage, the binder material was added and mixed at a low speed. After that, 80% of total water with 100% of the superplasticizer dosage was added and mixed at low-medium speed. In the third stage, the fine aggregates were added and mixed at low-medium speed. Finally, in the fourth stage, the remaining water was added until a fresh paste is formed, and the steel fibers were then added slowly and mixed at low speed to avoid fiber agglomeration. A summary of the mixing procedure can be shown in figure 2. Once the mix is ready for casting, the paste was placed in steel molds and mechanical vibration was applied for approximately one minute. The samples were then left in the molds for 24 hours and then were removed and exposed to the different curing regimes implemented in the study.

This study involved two main curing regimes which are water curing (WC) and hot air curing (HAC). For WC, the samples were removed from the molds and exposed directly to standard water curing conditions. For HAC, after the samples were removed from the molds at 24 hours, the demolded samples were left an additional time of 24 hours in ambient condition to ensure that the samples are completely dry before exposing them to HAC. This was mainly done to avoid any detrimental effect which can happen as a result of improper curing of HAC. Therefore, the samples were put in the oven after 48 hours of their casting and were left to cure in the oven at a temperature of 100°C.
2.3. Testing procedure
The compressive strength was conducted as per ASTM C 109-20 at a loading rate of 0.35 MPa/s on 50 x 50 x 50 mm specimens and was evaluated over a long-term period of 90 days. For the water cured samples, the strength was evaluated after a duration of 3, 7, 14, 21, 28, 56, and 90 days. For the HAC however, the samples were divided into two main groups. Group I samples were exposed to HAC for 48 hours, and the strength was evaluated at a 12-hour interval (0, 12, 2, 36 & 48 hours). Group II samples were only exposed to HAC for 24 hours and then removed from the oven and left to cure in ambient condition. The samples were then tested after a duration of 3, 7, 14, 21, 28, 56, and 90 days. This was mainly done to study the long-term effect of HAC on RPC compressive strength after being exposed to ambient conditions. Figure 2 summarizes the curing regimes implemented along with their testing event. Note that at each testing event at least 4 specimens were tested.

3. Results and Discussion
This section presents and discusses the compressive strength results of the three mixes evaluated in this study (CM, G30 & G15F15 mixes). The section is divided into three main subsections for each curing regime implemented. In each subsection, the effect of the incorporation of GGBS and ternary blends will be discussed.

3.1. Water Curing
Figure 3 presents the compressive strength results up to 90 days. As observed, the compressive strength of all mixes increases until 90 days; however, the rate of strength increase is different for the control mix as compared to the mixes incorporating SCM. The control mix (CM) exhibits the highest strength up to 56 days. After that, the G30 and G15F15 mixes attain the highest strength at 90 days. The sole effect of GGBS or combined with FA decreased the compressive strength noticeably until 28 days. The reported decrease reached up to 26% and the decrease margin reduced with time. Such behavior was expected as GGBS and FA are well known for the delayed hydration which demands time for the production of C-S-H. Nevertheless, at 90 days the SCM mixes attained comparable strengths to that of the control mix with a 4.3% difference. When comparing the effect of ternary blends of SF-GGBS-FA (G15F15 mix) compared to binary blends of SF-GB (G30 mix), the difference in compressive strength was comparable and the percentage difference between the two mixes did not exceed 8%. Despite the variations, all mixes attained a compressive strength of UHPC with strength exceeding 120 MPa at 28 days.
3.2. 12-hour HAC

Figure 4 presents the compressive strength development of the 12-hour increment of HAC up to 48 hours. As shown from the figure, HAC has a substantial influence on the strength of RPC and all mixes attained the strength of UHPC (>120 MPa) after 12 hours only of HAC. The control mix exhibited different behavior as compared to the SCM mixes. The strength for the control mix increased only up to 24 hours and then started to decrease while for the other mixes the strength continued to increase until 48 hours. For the control mix, the decrease observed after 24 hours, may denote that there is an optimal crystallization limit which when exceeded, crystallinity becomes undesirable, and the strength decreases [17]. Such behavior has previously been reported in studies that investigated the effect of autoclave curing on RPC strength [18], [19]. In these studies, both reported that the optimal autoclaving time was found to be either 8 or 10 hours depending on the mixes evaluated. After exceeding the optimal time, the strengths of the mixes start to decrease gradually. For the SCM mixes, the strength continued to increase until 48 hours as shown in figure 4 and this may be ascribed to the increased silica sources present in GGBS and FA as compared to cement. The optimal autoclaving time is mostly reported to be around 8 to 10 hours by most studies [2], however, the optimal HAC for different mixes incorporating different materials such as SCM still needs further study to be able to reach a solid conclusion regarding the optimal time. Overall, the effect of HAC on the compressive strength of RPC was significant for all the three mixes where each mix attained a minimum increase of 80% after 12 hours of HAC. Similar to the previous section, when evaluating the effect of the ternary blends used in this study, both the G30 and G15F15 mixes exhibited similar behavior with no noticeable difference between the two mixes.
3.3. 24-hour HAC + Ambient

Figure 5 presents the compressive strength development of the samples exposed to 24 hours of HAC and then left in ambient condition up to 90 days. For the compressive strength, when the samples were removed from the oven, the strength increased slightly up to 7 days and reached 160 MPa, and then started to decrease. No clear trend was observed for the control mix but the strength reported was in the range of 155 to 140 MPa. In contrast, the SCM mixes exhibited different behavior and the strength continued to increase up to 90 days for both the G30 and G15F15 mixes. This is probably due to the incomplete hydration of the GGBS and FA when removed at 24 hours only. Also, from figure 4, it was shown that the strengths of these mixes (G30 & G15F15) continued to increase until 48 hours which confirms the incomplete hydration of these mixes at 24 hours. This can therefore justify why the strength of the G30 and G15F15 mixes continued to increase under the ambient condition when they were removed at 24 hours only. Although at early ages of 3 to 28 days, the control mix had higher strengths (18%) than that of the SCM mixes, these mixes still attained the highest strengths over the long term of 90 days when left in ambient condition. The reported strength for each of the control mix, G30, and G15F15 mixes were 149, 156, and 157 MPa, respectively, at 90 days. Note that similar to the previous two subsections, the use of ternary blends did not noticeably improve the compressive strength as compared to the binary blends. Therefore, it cannot always be concluded that ternary blends will necessarily improve the strength when compared to binary blends. This will depend on the types of binder used. In this study, the SF-GGBS-FA produced similar results to that of the SF-GGBS. However, such a blend will likely perform better when compared to a binary blend of SF-FA only.

![Figure 5. Compressive strength development of hot air cured specimens.](image)

4. Conclusion

In conclusion, this study aimed to produce reactive powder concrete with ultra-high compressive strength using local materials in the UAE. To achieve this, dune and crushed sand were used in place of quartz which is the frequently utilized type of aggregates in RPC and was used with larger sizes of 150 µm–1.18 mm. The cement content was replaced with SCM and was reduced by 30% to 571 kg/m³. Three mixes were developed for the evaluation (CM, G30, and G15F15 mixes) and the study investigated 1) the effect of 30% GGBS on RPC strength, 2) the effect of ternary blends compared to binary blends (SF-GGBS-FA vs. SF-GGBS), and 3) effect of hot air curing compared to water curing.

The key findings of the study can be summarized as follows:

1. All mixes attained the strength of ultra-high-performance concrete with strength exceeding 120 MPa after 12 hours of hot air curing and after 28 days of water curing.
2. The use of SCM reduced the strengths of the mixes by approximately 28 and 18% at the early ages of 3 to 28 days of water curing and hot air curing, respectively. However, at later ages of 56 to 90 days, the strengths of these mixes were similar to that of the control mix.
3. The optimal curing time varied for the mixes investigated in this study under HAC. The control mix attained the highest compressive strength at 24 hours of HAC, while the G30 and G15F15 mixes achieve their highest strengths at durations exceeding 24 hours of HAC.

4. The use of ternary blends showed similar performance to that of binary blends (G15F15 vs. G30) and therefore it can be concluded that SF-GGBS-FA does not necessarily perform better than SF-GGBS.

Acknowledgments
The authors would like to thank the American University of Sharjah’s research office for their financial support.

5. References
[1] P Richard and M Cheyrezy 1995 Composition of reactive powder concretes, *Cem. Concr. Res.*, 25, pp 1501–1511
[2] S Ahmed, Z Al-Dawood, F Abed, M A Mannan, and M Al-Samarai 2021 Impact of using different materials, curing regimes, and mixing procedures on compressive strength of reactive powder concrete - A review, *J. Build. Eng.*, p 103238
[3] H seok Jang, H seok So, and S So 2016 The properties of reactive powder concrete using PP fiber and pozzolanic materials at elevated temperature, *J. Build. Eng.*, 8, p 225–230
[4] Y W Chan and S H Chu 2004 Effect of silica fume on steel fiber bond characteristics in reactive powder concrete, *Cem. Concr. Res.*, 34, p. 1167–1172
[5] K L Scrivener and R J Kirkpatrick 2008 Innovation in use and research on cementitious material, *Cem. Concr. Res.*, 38, pp 128–136
[6] B L Damineli, F M Kemeid, P S Aguiar, and V M John 2010 Measuring the eco-efficiency of cement use, *Cem. Concr. Compos.*, 32, pp 555–562
[7] S A Miller 2018 Supplementary cementitious materials to mitigate greenhouse gas emissions from concrete: can there be too much of a good thing?, *J. Clean. Prod.*, 178, pp 587–598
[8] K L Scrivener, V M John, and E M Gartner 2018 Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry, *Cem. Concr. Res.*, 114, pp 2–26
[9] S Ahmed, Y Alhoubi, N Elmesalami, S Yehia, and F Abed 2021 Effect of recycled aggregates and treated wastewater on concrete subjected to different exposure conditions, *Constr. Build. Mater.*, 266
[10] Z A Hasan, M S Nasr, and M K Abed 2021 Properties of reactive powder concrete containing different combinations of fly ash and metakaolin, *Mater. Today Proc.*, 42, pp 2436–2440
[11] J Liu, Z Ou, J Mo, Y Wang, and H Wu 2017 The effect of SCM and SAP on the autogenous shrinkage and hydration process of RPC, *Constr. Build. Mater.*, 155, pp 239–249
[12] Y Peng, S Hu, and Q Ding 2010 Preparation of reactive powder concrete using fly ash and steel slag powder, *J. Wuhan Univ. Technol. Mater. Sci. Ed.*, 25, pp 349–354
[13] H Yazici, H Yiğiter, A Ş Karabulut, and B Baradan 2008 Utilization of fly ash and ground granulated blast furnace slag as an alternative silica source in reactive powder concrete, *Fuel, 87*, pp 2401–2407
[14] N De Belie, M Soutsos, and E Gruyaert, RILEM State-of-the-Art Reports Properties of Fresh and Hardened Concrete Containing Supplementary Cementitious Materials State-of-the-Art Report of the RILEM Technical Committee 238-SCM, Working Group 4
[15] Z Yunsheng, S Wei, L Sifeng, J Chujie, and L Jianzhong 2008 Preparation of C200 green reactive powder concrete and its static-dynamic behaviors, *Cem. Concr. Compos.*, 30, pp 831–838
[16] P N Hiremath and S C Yaragal 2017 Influence of mixing method, speed and duration on the fresh and hardened properties of Reactive Powder Concrete, *Constr. Build. Mater.*, 141, pp 271–288
[17] S Ahmed, Z Mahaini, F Abed, M A Mannan, and M Al-Samarai 2022 Microstructure and mechanical property evaluation of dune sand reactive powder concrete subjected to hot air curing, *Materials*, 15, p 41

[18] H Yazici, E Deniz, and B Baradan 2013 The effect of autoclave pressure, temperature and duration time on mechanical properties of reactive powder concrete, *Constr. Build. Mater.*, 42, pp 53–63

[19] T Chen, X Gao, and M Ren 2018 Effects of autoclave curing and fly ash on mechanical properties of ultra-high performance concrete, *Constr. Build. Mater.*, 158, pp 864–872