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RESEARCH PAPER

Feasibility Study on Concrete Performance Made by Partial Replacement of Cement with Nanoglass Powder and Fly Ash

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Abstract

In this paper, the feasibility of using nanoglass as a partial replacement of cement in combination with fly ash was investigated. Three concrete mixtures made with fly ash and nanoglass as cement replacements were studied as a preliminary investigation. The first mixture contained 25% class F-fly ash (FA) and 0% nanoglass powder (NGP); the second mixture had 12.5% class F-FA with 12.5% NGP; while the third mixture had 0% class F-FA, with 25% NGP. In all the mixtures, the water-to-cementitious (w/cm) ratios were kept constant at 0.42. Fresh properties of each mixture were tested, which included air content and workability. Expansion due to potential alkali–silica reaction (ASR) was also tested, as well as mechanical properties such as compressive strength, tensile strength, and flexural strength. It was observed that the increase in NGP content beyond 12.5% in the presence of 12.5% class F-fly had a negative effect on the concrete fresh and mechanical properties. Overall, the addition of NGP enhanced the mechanical properties of the concrete, and the expansion due to ASR is less than 0.1% which is the threshold value.

Keywords Concrete · Cement · Fly ash · Nanoglass powder · Alkali–silica reaction

1 Introduction

The advent of nano-technology has shaped the face of material development for engineering purposes through the modifications of material microstructure to produce new hybrid materials with better properties. Despite the application of nanotechnology in other fields of engineering, the construction industry is yet to take full advantages offered. Particles having a dimension lesser than 100 nm are usually referred to as Nano particles. The properties of such materials are greatly altered because of their sizes.

The possibilities of reusing waste glass powder in concrete have been studied by numerous authors [1–3], with focus on the use of soda lime glass which contains about 70% SiO_2, 12% Na_2O, and 5% CaO. The high silica content of glass gives pozzolanic effect, while the Na_2O can result in ASR (alkali–silica reaction), if reactive aggregate is used in the concrete. The two major effects of NGP as replacement for ordinary Portland cement in concrete reported in literature are ASR and pozzolanic action. The ASR is known to have a negative action that causes expansion and pattern cracking in hardened concrete; while the pozzolanic action is considered positive because extra calcium silicate hydrate (CSH) gel is produced during secondary hydration of cement [4].

When glass powder of 0.75 μm size used as cement replacement in concrete showed no deleterious expansion nor swelling as reported by Du et al. [5]. When clear glass, brown glass, and green glass powder of 0.75 μm size were compared, the

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clear glass showed higher expansion, with the green glass having three times lower expansion than the clear glass, and the brown glass had nine times lower expansion. The justification for that was the existence of Cr_2O_3 in colored glass, but absent in clear glass [5]. When 30% liquid crystal display (LCD) glass powder with 3.37 fineness modulus was used in self-consolidating concrete as cement replacement, an increase in compressive and flexural strength, reduced permeability, and increase resistance to sulfate attack were reported [6]. The effect of glass sizes was investigated by Idir et al. [7], where glass powder with sizes higher than 1000 µm displayed higher expansion due to ASR, while best pozzolanic behavior was observed in glass powder with size range of 10–20 µm [7]. Similar results were observed when glass powder of 13 µm particle sizes was used as partial replacement for cement in concrete. A high pozzolanic reaction, improved microstructure, reduced adsorption and chloride permeability, and negligible expansion due to ASR were observed [8].

Glass powder and fly ash can be used simultaneously to modify the microstructure of concrete when used as partial replacement of cement, such modified microstructure led to a lower rapid chloride permeability coefficient when compared to plain concrete [9]. The fly ash modified concrete has a higher chloride binding capacity due to higher content of alumina present in fly ash, but the glass powder has a higher alkali content [9].

From the reviewed literature, the effect of glass powder on concrete properties is still a debatable issue, but the factors governing the behavior of concrete made with glass powder on concrete include glass chemical composition; particle size; and impurities or other chemicals added to glass for color. While many authors agreed that the SiO_2 content of glass being the highest constituent, is responsible for its pozzolanic behavior, Na_2O being the next highest constituent of glass is responsible for the ASR reaction, other authors have stated that both pozzolanic and alkalis behavior are due to the particle size of the glass powder.

There are two approaches to produce nanomaterials: the top down and the bottom-up [10]. In the top down method, the parent larger material is reduced by grinding or breaking down the particles to nanoscale without changing the parent material properties. In the bottom-up or molecular technology approach, new nanomaterials are engineered from atoms or molecular components through a process of assembly or self-assembly. Glass particle of nanoscale in the order of 0.1–10 nm has been invented for use in concrete and other allied engineering field [11].

Table 1 Chemical composition of cement, fly ash, and nanoglass powder

Component	Content %		
	Cement	Fly ash	Soda lime nanoglass powder
SiO_2	20.40	48.50	71.86
TiO_2	0.15	0.05	0.05
Al_2O_3	4.60	27.50	1.45
Fe_2O_3	3.50	10.50	0.71
MnO	0.05	0.04	0.02
MgO	1.20	1.30	2.04
CaO	64.90	5.76	6.58
SO_3	2.50	0.46	0.10
Na_2O	0.55	0.28	9.48
K_2O	0.00	2.68	0.74
P_2O_5	0.00	0.00	0.01
Na_2O_{ekv}	0.03	0.03	8.68
Loss on ignition	2.12	2.90	1.01

Fig. 1 Cementitious materials used

2 Experimental Procedures

2.1 Materials

The waste glass used in this study is Soda lime glass obtained from BRQ Inc., Texas, USA. The glass was crushed and grounded into nano-sized powder of average size 100 nm using the top down method, properly blended to ensure that no larger sizes were present that may act as coarse aggregate in the concrete mix. A type I/II low alkali Portland cement that met the chemical and physical specifications of ASTM C150 [12] was used in this study. The ordinary Portland cement (OPC) was obtained from CEMEX factory, and class F-FA was obtained as a by-product of coal, when burned and pulverized in electrical generating stations. The chemical composition of the cement, nanoglass powder, and fly ash is summarized in Table 1, and representative samples of the cementitious materials are shown in Fig. 1.

Locally available sand obtained from Fordyce Showers was used as fine aggregate. The specific gravity of the sand was 2.63 conforming to grading zone III as per ASTM C33 [13]. The coarse aggregate was obtained from Fordyce Showers with maximum nominal size of 10 mm. The aggregates were all in conformation to ASTM C33 specifications which ensure that they were well graded by avoiding voids between larger and smaller sizes.

A high range water reducer (HRWR) obtained from WR Grace ZYLA610 was used alongside WR Daravair 1000 as an air entrainment admixture in this study. These admixtures conform to ASTM C494 [14] (types F and G) and ASTM C260 [15], respectively.

2.2 Samples Preparation and Testing Procedure

2.2.1 Fresh Properties Tests

Three mixtures were considered in this study as a preliminary investigation of using nanoglass powder in concrete as a pozzolanic material. The first mixture was the control, and cement were replaced by 25% fly ash, the second mixture cement was replaced by 12.5% fly ash and 12.5% of nanoglass and in the third mixture, no fly ash was used and 25% of cement was replaced by nanoglass powder only. In addition to studying the behavior of partial replacement of cement with fly ash ad nanoglass powder, fresh property tests were carried out. The mixing was carried out in accordance to ASTM C192 [16]. Surface dried fine and coarse aggregates were poured into the mixer, thoroughly mixed, before a portion of the mixing water and a dose of admixture added. The cement, fly ash, and nanoglass powder, and remaining water were added as the mixing machine was in motion. When all materials had been integrated, the concrete was mixed for 3 min to obtain a uniform mixing of all the concrete ingredients. Samples were obtained to measure the slump and air content per ASTM C143 [17] and ASTM C231 [18], respectively. Details of the mixture proportions are shown in Table 2.

2.2.2 ASR Test

The ASR test was performed on prisms of 25 × 25 × 285 mm made from mortar having a water-to-cement ratio of 0.42 using the mixtures described in Table 2. Steel molds were used to cast the prisms, covered by plastic and removable tapes, and cured in a moist room at 23 °C ± 2 °C, and 98% relative humidity (RH) for 24 h. After demolding, the reference length was taken by a digital length comparator as prescribed in ASTM C490 [19] and thereafter cured in water at 80 °C and 65% RH for 24 h. The specimens were then kept in air and water-tight polypropylene containers which was submerged in a 1 N NaOH solution and placed in an oven

Table 2 Concrete mixture proportions

Mixes	w/cm	Unit weight (kg/m^3)						HRWR (kg/m^3)	Air entrained (kg/m^3)	Air (%)	Slump (mm)
		Water	Cement	NGP	Fly ash	Fine agg.	Coarse agg.				
MI (0% NGP + 25% FA)	0.42	141.0	251.8	0.0	84.0	744.3	1106.1	1.68	0.04	3.60	63.5
MII (12.5% FA + 12.5%NGP)	0.42	141.0	251.8	42.0	42.0	744.0	1106.1	1.68	0.04	2.30	76.2
MIII (25% NGP + 0% FA)	0.42	141.0	251.8	84.0	0.0	744.3	1106.1	1.68	0.04	3.60	71.1

under convection at 80 °C ± 2 °C. New length readings were then taken at 14 and 28 days. The new length was recorded for each specimen and the expansion calculated, using the zero day as reference length. The average of three specimens was considered in the calculation of the ASR test.

2.2.3 Mechanical Properties Tests

The mechanical properties tests conducted include compressive strength, split tensile and flexural strength. The compressive strength test was conducted on three 100 × 200 mm cylindrical specimens at 7th, 14th, and 28th day after moist curing as specified in ASTM C39 [20]. The specimens were loaded until failure under axial load, and the average of the compressive strength of three cylinders was taken as the concrete strength. Similarly, the split tensile test was conducted on three cylinders of 100 × 200 mm cylinders at 7th, 14th and 28th day in reference to ASTM C496 [21], the tensile strength considered was the average of the three tensile strength at each testing age. The flexural strength test was conducted on concrete beam of 150 × 150 × 525 mm, using four-point loading procedure as specified in ASTM C78 [22] after 28th day of moist curing. The specimens were loaded on the face perpendicular to the direction of casting. The loads were applied continuously until rupture, while measuring and recording the location and origin of the fracture. The simple beam bending equation was used to calculate the concrete modulus of rupture.

3 Results and Discussion

3.1 Cement Replacement by Fly Ash and Nanoglass Powder

3.1.1 Fresh Properties

The two fresh properties measured in this study were flowability and air content as shown in Table 2. The flowability was measured using slump test. MII displayed the highest slump of the three mixes. The particle shapes of fly ash and nanoglass powder when viewed under a scanning electron microscope (SEM) are shown in Fig. 2. The NGP particle shape is angular, while FA is spherical. These particle shapes explain the flowability behavior of the concrete mixtures. The spherical shaped particle behaves as ball bearings within the fresh concrete mix and produces a lubricating effect by reducing the frictional forces within the concrete mixtures. In contrast, NGP, are angular with low water absorption capacity, huge surface area and smoother surfaces. The interaction between the two particles affected the workability of the mixtures as presented in Table 2. Although fly ash particles have spherical shape with ability to improve workability, they partially absorb part of the mixtures' water, and reduce the water needed for lubrication leading to reduction in workability. It should be noted that the reduction in workability occurs when high percentage of fly ash is used, usually above 20% [23]. In contrast, nanoglass powder with angular microstructure with lower water absorption reduces workability because of its shape. The combination of fly ash and nanoglass powder (MII) displayed the highest workability compared to mixtures containing either only fly ash and nanoglass powder. The observed results are in agreement with other studies [24, 25].

For normal concrete made without supplementary cementitious materials, the recommended entrained air ranges

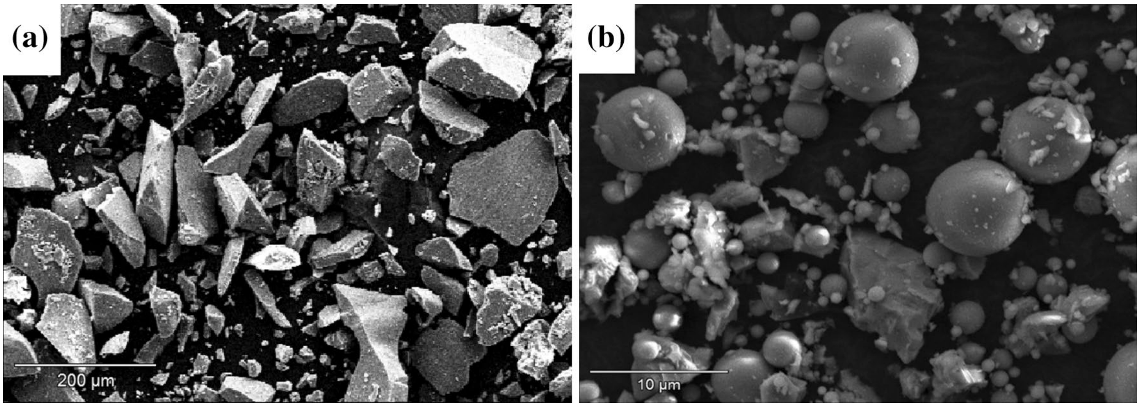


Fig. 2 SEM images of **a** NGP. **b** Fly ash

between 4 and 7% of the volume of the concrete [26]. These air pockets serve as pressure relief for the concrete during freeze and thaw cycles, especially for concrete exposed to cyclic freezing and thawing conditions. As shown in Table 2, MI and MII both have 3.6% entrained air. The increase in workability offered by fly ash and NGP damaged the air pockets in the concrete, as evident in MII with the highest workability, but lowest entrained air. In addition, the unburned carbon in fly ash and nanoglass powder adsorbs the air-entraining agent thereby reducing the amount of entrained air in the concrete. To increase the entrained air of the concrete mixtures, it is suggested to increase the dosage of the air-entraining agent, without reducing the workability.

3.1.2 Mechanical Properties

The compressive strength results are shown in Fig. 3 and summarized in Table 3 at different ages. Using MI as reference, MII and MIII displayed a higher compressive strength. During the first stage of hydration (reaction of cement with water), calcium silicate hydrate (CSH) and calcium hydroxide (CH) were produced. In the second stage, Silica from fly ash and NGP react with the CH to produce extra CSH that will result in a denser microstructure. As shown in Fig. 3, MI and MIII displayed lower compressive strength at age 7 days. The loss in early strength may be attributed to the reduction of cement by replacing it with fly ash and NGP, rather than slower hydration and pozzolanic actions of fly ash and nanoglass powder. The increase in compressive strength was observed because of the pozzolanic behavior of nanoglass powder and fly ash. MII displayed the highest compressive strength at the 28th day due to the pozzolanic actions of fly ash and nanoglass powder; fineness of nanoglass powder and densified microstructure of the concrete mixture. Increasing the percentage of nanoglass powder in the concrete mixtures led to a lower strength as observed in MIII. Incorporating glass powder up to 15% with average particle size of 3 µm in concrete with 0.4–0.5 water-to-cementitious ratio led to a reduction in 28th day compressive strength [2, 27, 28]. While it is necessary to conduct more studies on the strength reduction of the concrete mixtures beyond 12.5%, the availability of NGP is a concern, because of its cost. However, the authors are currently conducting more studies to further investigate the overall behavior and properties of concrete made with NGP.

A similar trend was observed in the tensile strength test (Fig. 4). The tensile strength for MII at 14 days was higher than the other specimens (MI and MIII) as shown in Table 3. While, at 28 days the tensile strength of MII

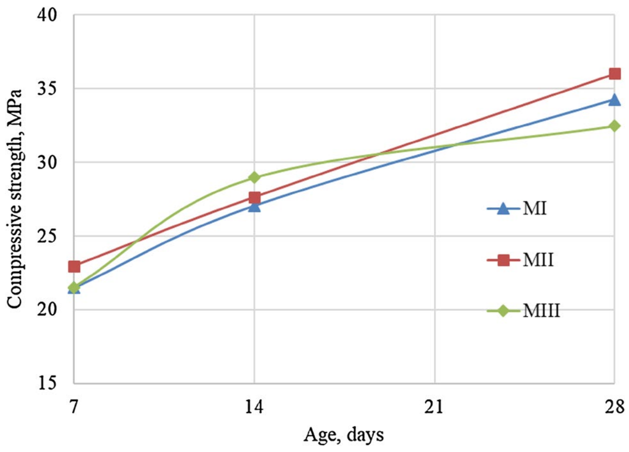


Fig. 3 Compressive strength

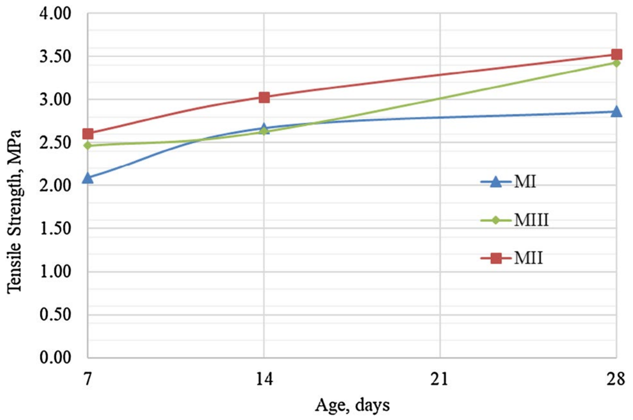
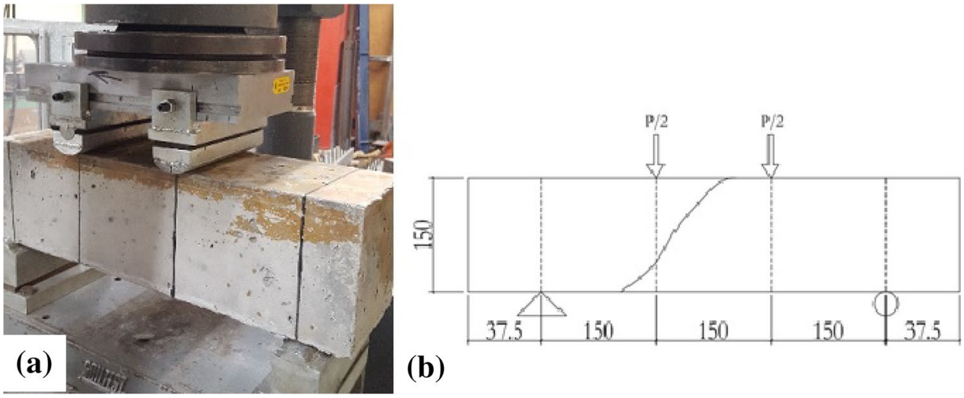


Fig. 4 Tensile strength

Table 3 Summary of specimens' compressive strengths

Specimen ID	7th day	Standard error	14th day	Standard error	28th day	Standard error
Compressive strengths (MPa)						
MI	21.5	0.8	27.0	0.7	34.3	1.2
MII	23.0	0.3	27.6	0.6	36.0	0.9
MIII	21.5	1.8	29.0	1.7	32.0	3.2
Tensile strengths (MPa)						
MI	2.1	0.2	2.7	–	2.7	–
MII	2.6	–	2.9	0.1	3.0	0.1
MIII	2.5	–	2.6	0.3	2.6	0.2

Fig. 5 Four-point loading procedure. **a** Laboratory setup. **b** Schematic setup (dimensions are in mm)



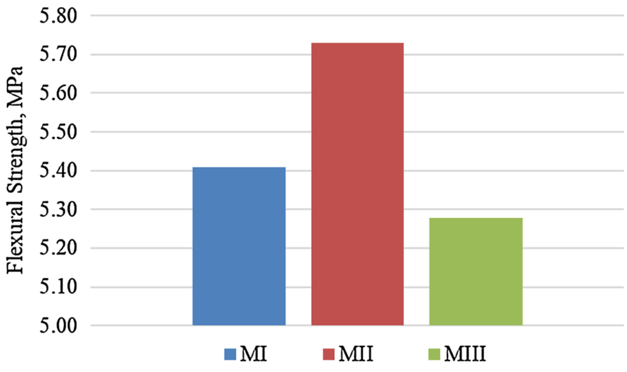


Fig. 6 Flexural strength of concrete specimens

and MIII were higher than the control mixture MI. The maximum tensile strength and compressive strength are 3.53 and 3.6 MPa, respectively, for MII.

The four-point bending was used to determine the flexural strength of the concrete mixtures. It was selected over three-point bending because a larger area of the beam is subjected to a maximum stress against subjecting only one section directly under the maximum load in three-point bending. Since the maximum stress is directly related to crack initiation and flexural strength, the maximum load and crack locations were recorded for this test as shown in Fig. 5.

The results of the flexural strength are shown in Fig. 6. As previously observed, MII had the highest flexural strength, when compared to other mixtures. It could be stated that nanoglass powder exhibits pozzolanic properties which result in improved compressive, tensile and flexural strengths as observed. However, it was also found that the compressive, tensile, and flexural strengths decreased when the nanoglass powder exceeded 12.5%, likely due to the aggregation of nanoglass particles that could not be evenly dispersed during mixing. This NGP particles accumulation affected the microstructure and homogeneity of the concrete composite behavior.

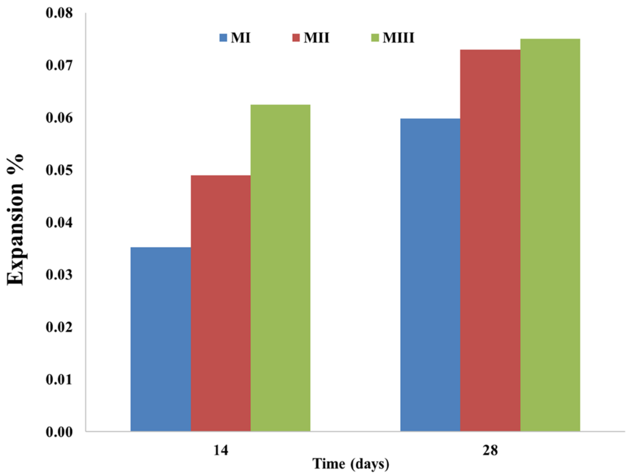


Fig. 7 ASR (alkali–silica reaction) expansion

3.2 Alkali–Silica Reaction (ASR)

The accelerated mortar bar test (AMBT) procedure was followed to determine the suitability of combining the supplementary cementitious materials (SCM) and aggregate [29]. The results obtained are shown in Fig. 7, where MI had the lowest expansion at 14th and 28th day, corresponding to 0.035 and 0.059%, respectively. It should be noted that ASR expansion increases as NGP content increases, even though the maximum expansion is lesser than 0.1%, which is the limit given for nonreactive SCM, OPC and aggregate combination at 14th day [29]. It could be stated that nanoglass powder can be used as replacement for fly ash, since there is no significant increase in the expansion of MII and MIII. The need to replace fly ash arise from its heterogenous properties which depends on its source. The burning of coal and hydrocarbons for energy has been described as a major source of carbon emission around the world as evident through global warming and rise in ocean level. As stricter enforcement on coal burning is being expected around the world, the concrete industry therefore needs to look for alternative but affordable material that can be used to replace fly ash. The observed ASR result is consistent with Federal Highway Administration (FHWA) results [23]. It should be noted that both particle size and chemical composition of glass powder affects the alkali–silica reaction in concrete; while finer glass particles at micro level exhibit considerably lower expansion; pozzolanic behavior increases as fineness increases.

The increase in expansion as observed is due to the higher amount of SiO_2 present in the glass powder. The unavailability of experimental results on effects of nano-sized glass powder in concrete made it difficult to verify the observed results, but other authors [30] have concluded that fine particles of glass powder tend to relatively increase the pozzolanic reaction with OPC.

4 Conclusions

The feasibility of cement replacement with nanoglass powder was studied and presented in this paper. It can be stated that the mixture with 12.5% fly ash and 12.5% nanoglass powder performed better than other mixtures based on the compressive strength, tensile strength, flexural strength, and expansion due to alkali–silica reaction (ASR). As the nanoglass powder content increases, a reduction in compressive, tensile and flexural strengths were observed. The results of the ASR implied that increasing the nanoglass powder content does not significantly affect the detrimental expansion, that could lead to durability problems, when concrete is exposed to harsh weather. Based on this study, the partial replacement of cement with nanoglass powder has a potential to reduce the use of cement, reduce global carbon emission, and reduce the cost of recycling and disposal of waste glass materials.

The results presented in this study are currently being extended by the authors to investigate the effect of nanoglass powder on concrete properties. The studies will focus on mechanical and long-term durability properties of the concrete made with NGPs. It is expected that as more efforts are being geared toward glass recycling, the recycling cost would be justified if recycled glass found application in concrete production with better properties and at a lower cost.

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