

Effect of thermal shock on the grates of improved charcoal cook-stoves made from different materials



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ABSTRACT

From the current literature on cook stoves, it remains unclear on which is the best temper and the alternative soils that can be used in the production of charcoal cook-stoves that are resistant to thermal shock. To this end, a study was conducted to determine which soil type and mixing ratio that can produce the highest thermal shock resistance when used as grates. The grates made of clay, red and anthill soils each mixed with shale rock in ratios of 1:0; 1:1; and 3:1 were compared. The grates were fired and then heated in a furnace set at 400 °C for 1 h and subjected to two cooling treatments; rapid cooling by quenching in water and cooling at ambient temperatures, for seven subsequent cycles after being heated. The shock resistance for all the grates made from different soil types and different mix ratios was measured based on crack initiation and propagation according to ASTM C1525-04 standards. The results showed that clay soil mixed with shale rock in the ratio of 3:1 had the highest thermal shock resistance with no crack initiation throughout the heating and cooling cycles, followed by anthill soil mixed with shale rock in the ratio of 1:1. Therefore, charcoal stove users and manufacturers can expect a better quality product with high durability if shale rock is used to temper the cook-stoves in comparison to burnt bricks that are currently commonly used in Uganda. The method used in this work can be applied in other regions to come up with more material ratios that are resistant to thermal shock.

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Introduction

Due to the increasing population and cost of household fuel for heating and cooking, the demand for charcoal and firewood continues to increase pressure on forest and woodland resources as the main source of fuel. The high demand coupled with poor extraction and utilization methods have led to increased deforestation. Improved Cook Stoves (ICS) with capacity to save on the wood fuel required per cooking cycle been suggested as a remedy to curb the high rate of deforestation resulting from fuel wood extraction (Bhattacharya & Salam, 2000; Jetter & Kariher, 2009). These ICS are becoming popular because they can achieve low fuel consumption and offer better cooking efficiency while reducing on the flue gases and smoke within the kitchen space (Mehetre et al., 2017).

At present in Uganda, ICS making is an expanding enterprise in the informal sector. However, several challenges exist such as the appropriate material for stove construction to achieve minimal heat losses and longevity of use. In most cases, the outer shell of the cook stove remains intact for a longer time while the grate which holds the burning fuel wares out faster. Fig. 1 shows some of the abandoned charcoal cook

stoves whose outer shells are intact but the grates are no more as compared to those with still working grates. The stoves with broken grates render them useless except if there was a way to replace the grates.

According to Chaplin (1983), materials used in the construction of combustion chambers of cook stoves should be selected based on their thermal shock resistance. This factor greatly determines the life span of the charcoal cook stove. Possibly, most of the stoves failing to serve their intended lifespan are made of materials whose resistance to thermal shock is inferior. Tite (2008) reports that there are apparently many alternative clays and tempers that can be used in production such that the resulting product adequately satisfies the strength, toughness and thermal shock resistance. However, information regarding the optimal mixing ratios to achieve a product with the highest resistance to thermal shock remains scanty. Also, access to standardized testing is limited for many informal stove producers whose products reach the market (World Bank, 2014).

In a cooking stove, thermal shock is commonly caused by spillage of water on the surface of the hot stove mostly during the cooking activities. The surface of the grate expands more rapidly than the interior when it is heated, and as a result, the surface is subjected to tensile stress whereas the interior is subjected to compression stress (Brontisky & Hamer, 1986), when there is spillage of water into the hot stove cracks develop in the structure due to thermal shock. To this

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end, the resistance of stove structural materials to thermal shock is a very essential performance index that predetermines the stove's service time and lifespan (He et al., 2017). However, no studies have been done to test the thermal shock materials used in making grates. Empirical testing of the materials used to make the grates for improved cook stoves is necessary to improve stove combustion chamber design and enough longer service life (Bryden et al., 2006). To address the knowledge gap, this work tested several soil materials mixed with shale rock in different ratios as an additive for their thermal shock resistance with an aim of selecting the best material combination for mass production of ICS grates by the local artisans. The research premise was that identifying a good mix of materials that could prolong the service life of the grate and this could become an innovative step towards increasing adoption for use of ICS whereby instead of complete abandonment of the damaged stove, end users can buy and replace the broken grates and avoid the cost of buying a new cook stove.

Materials and methods

Material collection and preparation

Clay soil denoted as "C" was collected from Mukono District (E: 32.729731, N: 0.370153) while red soil denoted as "R" and anthill soil denoted as "A" and normally called termite mold, were collected from Wakiso District. Shale rock denoted as "S" that was used as a temper was collected from a stone quarry also located in Wakiso District (E: 32.651228, N: 0.337356). All the soil samples and temper were sun dried for 3 days, crashed and sieved to fine particles with a sieve of 2 μ. Each soil type was then mixed in water to make a mold by pressing until soil stickiness on the legs was minimal. The moulds were kept in air-tight bags for two weeks to cure in a similar manner as practiced by the local artisans who make charcoal cook stoves from clay soil in the area.

Experimental setup

The cured dough was mixed with shale rock in ratios shown in Table 1. A mixed sample of clay soil and crashed fired brick was used as the control. Crashed bricks are denoted as the "B" material. These materials (control) were obtained from local artisans producing charcoal stoves in Wakiso district. The eventual material mixtures that were used in the production of the experimental grates were denoted as C:S, A:S, R:S and C:B representing Clay + shale rock, Anthill soil + shale rock, Red soil + shale rock and Clay soil + crashed bricks in different mix ratios, respectively as shown in Table 1. The experimental grates were molded from these materials using a 12 cm internal diameter and 2 cm thickness metallic ring. Although cook-stoves on the market have grates with diameters in the range of 20–24 cm, the 12 cm diameter used for the experimental ones was dictated by the size of the combustion chamber of the furnace that was used to heat them as it could fit grates not

Table 1
Experimental setup showing the material combinations for cook-stove grates.

Sample	Ratio	Number of grates
C:B (control)	unknown	8
C:S	1:0	6
R:S	1:0	6
A:S	1:0	6
C:S	3:1	7
R:S	3:1	7
A:S	3:1	7
C:S	1:1	8
R:S	1:1	8
A:S	1:1	8

Note: the exact ratio of clay soil to fired brick (C: B) could not be established as the stove manufactures were not willing to reveal it. C:B stands for the material composition of clay and crashed brick as the temper and C:S, R:S, and A:S for clay, red soil and anthill soil with shale rock as the temper respectively.

>12 cm. In each grate, 4 holes were made using a 2 cm external diameter hollow plastic pipe 30 min after air drying. The grates were further air dried for 14 days and thereafter sun dried for 5–7 h for complete drying. It was worth noting however, that the drying time could be longer depending on the time of the year drying is being done. The time mentioned above corresponds to a dry period (Jan-March or June to July) but it could be longer by a week more during the wet periods (April to May or September to November) when the sunshine hours are shorter and temperatures tend to be low. After drying the grates were fired in wood powered kiln and then after subjected to the thermal shock resistance tests.

Firing of the cook-stove grates

The grates were fired from a round kiln made of bricks. Inside the kiln, the grates were randomly packed on the kiln bed. Firewood was used to light-up the kiln and initiate the grate baking process. After 1 h from the start of firing, the kiln temperature was measured using an infrared thermometer and had reached 459 °C. Within 5 h of kiln firing, temperatures reached 580 °C and the firing was stopped to initiate cooling. After cooling, the grates were offloaded using metallic tongs. This allowed the grates to cool at ambient temperature. The grates' survival rate was calculated using Eq. (1). The cold grates were then taken for laboratory analysis in the materials laboratory in the Department of Mechanical Engineering, at Makerere University. Fig. 2 shows the different soil types that were used in the study while Fig. 3 shows kiln firing and samples of the fired grates in the ratios of 1:0, 1:1 and 3:1 for each of the three soil types to shale rock.

$$SR = \frac{N_i - N_d}{N_i} \times 100\% \tag{1}$$

where SR is the survival rate, N_i is number of grates put in the kiln and N_d is number of grates damaged whiling firing.



Fig. 1. Some of the charcoal cook stoves no longer in use due to damaged grates as compared to those with working grates.

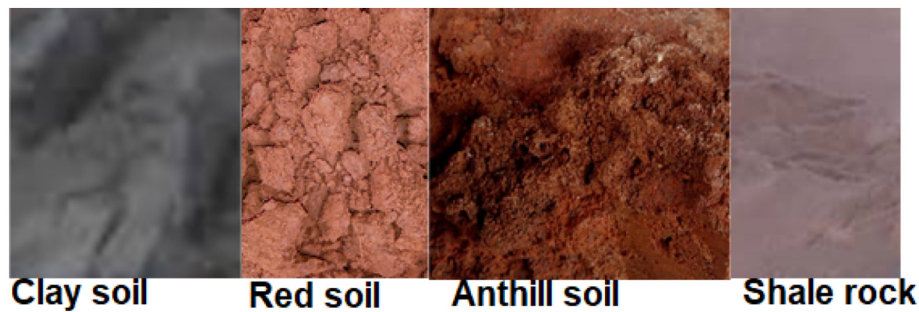


Fig. 2. Soil types used in the study.

Figs. 2 and 3 show the different coloration of the soils and grates. The different colour shades of the fired grates could be attributed to the soil type and the admixture that was incorporated. The dark-coloured grates (as seen in A:S 1:1-3:1, R:S 1:1-3:1 and C:S 1:1-3:1) are the ones where temper material was added. These are much darker than the control (C:B) and pure clay (C:S 1.0). Conversely, grates of pure anthill soil (A:S 1:0) and pure red soil (R:S 1:0) were more reddish compared to those with temper.

Determination of the effect of thermal shock on cook stove grates

The determination of resistance to thermal shock was done according to ASTM C1525-04 standards following a detailed procedure as reported by Awaji and Choi (2012). Briefly, already fired grates for each batch (different material mix) were placed into a furnace and heated to 400 °C for 1 h. After 1 h, half of the grates were quenched in a water bath at room temperature. The other half was let to cool at room temperature without quenching for 2 h. For each of the treatments (material mix), 7 cycles of heating and cooling were done, followed by visual analysis at the end of each cycle using a magnifying glass (x 10 magnification) for crack detection. It is important to note that before switching to the next cycle, the wet quenched grates would be oven dried at 110 °C for 30 min to drive off water absorbed during the previous wetting. For visible cracks, a nylon thread was used to trace crack development and thereafter stretched out on a ruler to measure the length of the crack and any increase in length of the cracks during the subsequent cooling cycles. The percentage increase in crack length was calculated by getting the difference between the final and initial crack length divided by the value of the initial crack length and then multiplied by a hundred to obtain a percent measure as shown in Eq. (2). The length of the longest crack was determined from

the incremental lengths obtained from the difference between the length of the crack before heating in the furnace and the length of that crack after quenching and or room temperature based on the expression in Eq. (3).

$$cl = \frac{l_f - l_i}{l_i} \times 100\% \tag{2}$$

$$l_c = l_{qa} - l_h \tag{3}$$

where; cl is percentage crack length increase, l_f is the final crack length in cm, l_i is the initial crack length in cm, l_c is length of the longest crack, l_{qa} is length after quenching or ambient cooling and l_h is length of crack before heating.

Results and discussion

Survival rate of cook stove grates after firing

Eq. (1) was used to find the Survival rate of the cook stove grates. Fig. 4 shows the survival percentage of the different soil materials at varying temper ratios. It shows that grates from clay mixed with shale rock in the ratio of 3:1 had the least survival rate.

Effect of thermal shock on crack initiation after quenching or ambient cooling

Fig. 5 presents the number of cracks that developed in the seven subsequent cycles of quenching or room temperature cooling for each category of grates that were tested. Results generally show that there were no cracks seen in the control and most of the grates from other mixtures

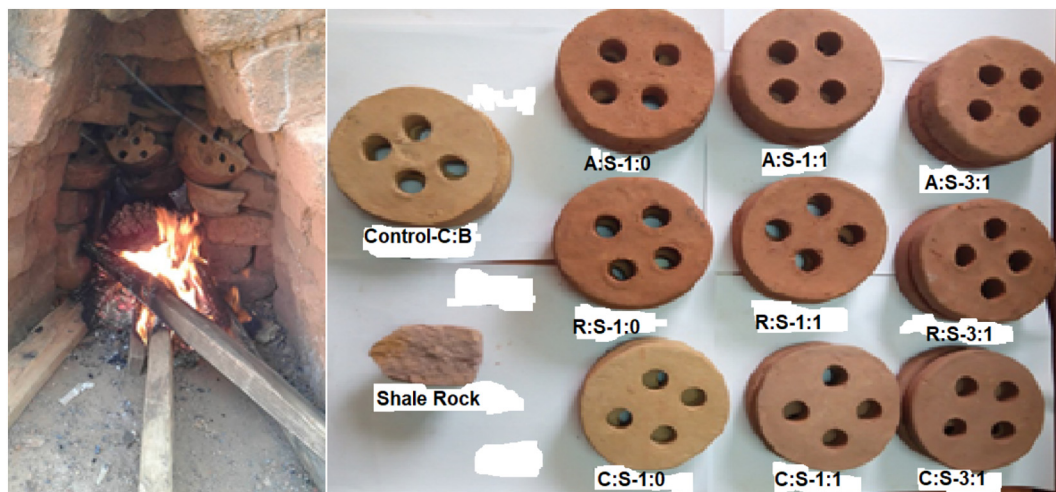


Fig. 3. Kiln firing of cook stove grates and samples of the fired grates.

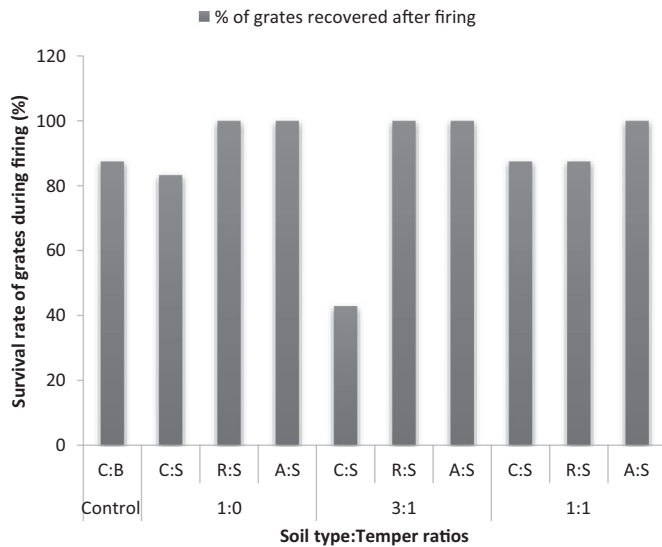


Fig. 4. Percentage of grates that survived during firing.

when cooled under room temperature with the exception of R:S 1:1, 3:1 and A:S 1:0, 3:1 grates. This implies that if there were no water spills on cook stoves during cooking, they would serve their economic life. Economic life refers to the time the cook stove lasts while serving its intended purpose. Realistically however, cook stoves suffer from water and soup spills during cooking which result into thermal shock that affects their economic life. Therefore, considering the grates that underwent quenching (used as a proxy for water spills), grates of clay mixed with shale rock (C: S) in the ratio of 3:1 were found to have no observable cracks throughout the seven cycles of heating and cooling by quenching. In comparison with the control (C: B), it was observed that under quenching, 1 crack developed in the first cycle, and the number increased to 2 after the second quenching. The number of cracks did not change until the seventh cycle of quenching when they increased to 5. It was also observed that grates from clay mixed with shale rock in the ratio of 3:1 dried very fast when they got into contact with water compared to the control grates. This finding suggests that the low permeability of the shale rock improved the water proofing properties of the grate (King, 2020). Furthermore, the results suggest that shale rock is a better temper material in cook stoves compared to burnt broken bricks which are commonly used by local artisans.

After clay mixed with shale rock (3:1), the second best to withstand thermal shock were grates produced from anthill soil mixed with shale

rock (1:1). Only 2 cracks were observed after the sixth quenching cycle and no other cracks developed in the seventh cycle. Since the cook-stove durability protocol by GACC (2014) recommends 5 cycles of quenching, it implies that in areas where clay soil is not readily available or where it has been depleted, anthill soil can serve the purpose if available for making cook stoves that are resistant to thermal shock.

Effect of thermal shock on crack elongation after quenching or ambient cooling

Fig. 6 shows the length of cracks in the respective cook-stove grates per heating and cooling cycle. According to the cook-stove durability protocol by GACC (2014), a crack is considered minor if it was <2 cm and major when >2 cm. The 3:1 clay to shale rock grates exhibited the highest resistance to thermal shock since they never developed any crack for all the seven cycles. However, considering 5 cycles as recommended by the cook-stove durability protocol, grates from the control (C:B), pure clay (C:S 1:0), pure red soil (R:S 1:0), anthill soil (A:S 1:1 and 3:1) presented minor cracks (< 2 cm in length) or had no crack by the end of the 5th cycle. This indicated higher resistance to thermal shock. On the other hand, C:S 1:1, R:S 1:1 and R:S 3:1 grates had major cracks (> 2 cm in length) after the second cycle of quenching. This implied that these particular material ratios have low resistance to thermal shock. Given that some grates with low temper concentration were better than those with higher temper concentration our results are in contradiction with earlier studies by Tite (2008) who reported that higher temper concentrations increased resistance to thermal shock. Hence forward, our result suggests that resistance to thermal shock is not only a function of temper concentration but probably, also type of soil being used.

Fig. 7 shows the percentage increase in crack length following heating and quenching or room temperature cooling of grates after every cycle for seven subsequent cycles of cooling. Although the number of cracks developed in the control grates remained constant from the second to the seventh cycle as already explained in *Effect of thermal shock on crack initiation after quenching or ambient cooling Section*, the length of the developed cracks did not remain constant. As can be seen from Fig. 7 there was an increase in crack length by ≥20% after every cycle of heating and quenching for the grates that were made from clay and ground burnt bricks (the control). It should be noted that clay and ground burnt bricks are the commonly used materials by local artisans involved in commercial cook stove manufacturing. Therefore, this increase in crack length after almost every cycle of heating and quenching proves why the cook stoves on the market cannot last longer when in use because ground burnt bricks may not be the best temper to use in cook stove making. On the other hand, shale rock as a temper seemed to provide the highest resistance to thermal shock

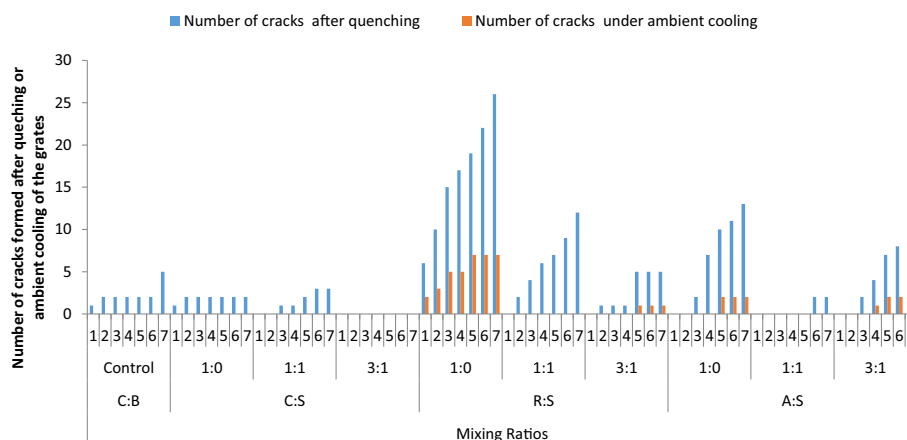


Fig. 5. Crack development in grates subjected to different cooling regimes. NB: Numbers 1 to 7 on the x-axis represent cooling cycles.

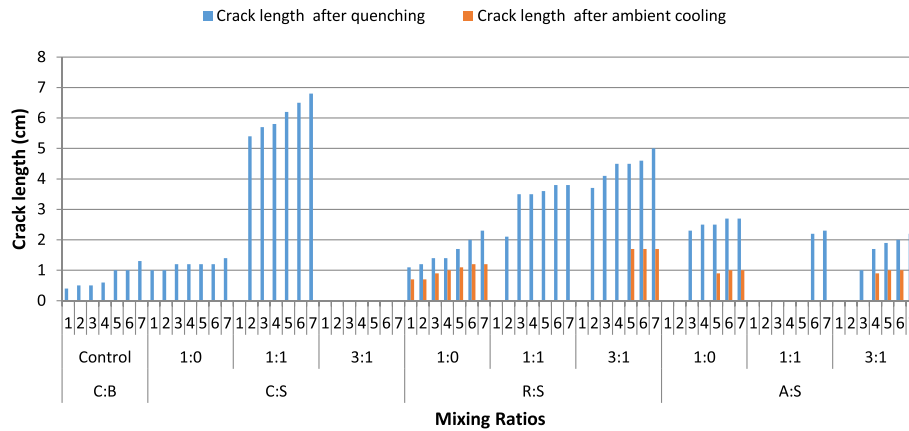


Fig. 6. Crack length (cm) in grates after every cooling cycle.

when mixed with clay in the ratio of 3 parts of clay and one part shale rock. When shale rock was not added there was an increase in crack length for grates of pure clay, red soil and anthill soil. For pure clay soil grates an increase of 17% in crack length in the seventh cycle was observed while in red soil and anthill soil grates without shale rock, an increase of 28.6% and 11.1% in crack length was recorded respectively, even in grates cooled under room temperature.

Results further suggest that when anthill soil is mixed with shale rock in the ratio of 1:1, the observed increase in crack length was minimal compared to the rest of the tested samples excluding the grates from the clay-shale rock mixture in the ratio of 3:1. The present study therefore, suggests that utilizing the relatively abundant shale rock mixed with clay or anthill soils could be a potential temper material in manufacturing highly thermal shock resistant cook-stoves compared to the current practice of using of ground burnt bricks. In this regard, the economic life of stoves would be increased resulting into value for money on the side of the charcoal cook-stove users.

Conclusion

This study set out to evaluate the thermal shock resistance of different commonly used materials for making grates in ICS in Uganda. From the experimental results the following conclusions can be drawn.

- The current materials (clay soil and burnt bricks) used in the manufacture of charcoal cook-stoves have less resistance to thermal

shock. The, cook-stove grates from clay soil mixed with ground burnt bricks have high susceptibility to crack initiation and elongation when subjected to subsequent heating and quenching cycles.

- Grates that were made from clay soil and shale rock in the ratio of 3:1 had the highest thermal shock resistance following heating and quenching cycles. This was followed by anthill soil and shell-rock in the ratio of 1:1.
- Utilizing the relatively abundant shale rock mixed with clay or anthill soils could be a potential temper material in manufacturing highly thermal shock resistant cook-stoves compared to the current practice of using of ground burnt bricks. In this regard, the economic life of stoves would be increased resulting into value for money on the side of the charcoal cook-stove users.
- The results reported in this work are only generalizable on the tested materials only. However, the testing procedures employed were based on standard and international protocol namely cook-stove durability protocol by GACC (2014), and American Standard Testing Methods on Cook Stoves (ASTM C1525-04). This implies that following the methods in this work, other materials in different regions may be tested for their resistance to thermal shock

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

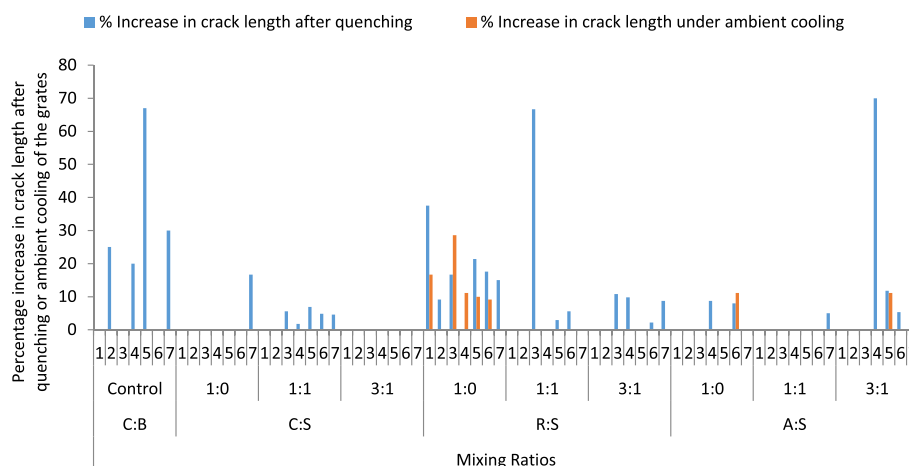


Fig. 7. Percentage increase in crack length after quenching or room temperature cooling.

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