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Responses to referee comments

Referee #3: Anonymous

I have two primary suggestions for revision 1) place the findings and work in the context of a subcritical to critical cracking conceptual framework from the beginning 2) considerably reorganize/simplify the writing of the text so that the hypotheses, results and conclusions more linearly fit together. Below are my comments regarding these two primary points and also some other minor issues.

In order to address the first part of the Reviewer's suggestion, we have made the following changes to the Introduction section:

- Introduce attrition mechanisms as chipping and fragmentation (which includes a discussion of fatigue failure as a form of fragmentation); we emphasize the difference between chipping and fatigue failure
- Cast the aforementioned attrition mechanisms in terms of subcritical and critical cracking – where fatigue failure is a subcritical mechanism and fragmentation is a critical one
- Edit introduction for clarity and readability

And the following changes to the Discussion and Conclusions section:

- Discuss our results in terms of subcritical and critical cracking, including the observation of a continuous, non-linear transition from subcritical to critical
- Emphasize that chipping is not subcritical cracking... it's a limit where something different is happening. No system-spanning cracks EVER emerge, only small cracks at corners.
- Edit discussion for clarity

We have also made changes to the text in an attempt to streamline and simplify the narrative to improve readability for the reader.

1) Placing the results in the context of subcritical vs. critical cracking
• It is not clear what the difference between "chipping and fatigue failure" are from the introduction (or really even in the discussion). The introduction focuses on the former, but appears to say (pg 4ish) that fatigue is somehow a separate mechanism. There does appear to be a clearer explanation in the discussion. Move this to the intro. But do these compressional 'chipping' cracks not continue to grow then by fatigue (subcritically)?
As mentioned above, the discussion of fatigue failure has been improved by directly addressing it earlier in the introduction section. This change to the text takes portions of the discussion to clarify the information provided about fatigue failure and how it differs from chipping. These

changes directly address the difference between chipping and fatigue failure, since chipping is NOT subcritical cracking.

Chipping appears as a limit, where the particle NEVER makes a crack that propagates through it and ONLY makes these small chips. Of course we cannot actually do infinite collisions, but this idea that there is a low energy/hard particle limit where only small chips can be made – and a subcritical crack never propagates through the material – is supported by the numerical simulations of Pal et al. (2021) that are discussed in the text. This was also proposed from theoretical considerations by Ghadiri and Zhang (2002).

• Overall, are you not in fact observing a transition from 'subcritical' to 'critical' regimes in your data? i.e. QuasiStable/progressive – vs. unstable crack growth for a given impact? The initial 'chipping cracks' at the contact zone are the first to grow once a subcritical threshold is met? Then, more growth sets in at intermediate energy? Then failure?
See discussion above.

• From fracture mechanics experiments and theory (some of which is mentioned in the discussion), we know this relationship (subcritical to critical) is similarly non-linear, would produce the reduction in strength that you observe, and is known to be a "continuous phase" transition (see reviews like (Brantut et al., 2013).
Discussion of our observations as a continuous phase transition from subcritical to critical regimes, which has non-linear behavior, has been incorporated into the discussion/conclusions section.

We wish to point out that Basquin's law (and the related Paris' law) are the more direct connections to make in terms of a power-law relation that would indicate a continuous type of phase transition. We agree that a more direct connection between the our findings, the Pal et al. (2021) numerical results, and the well known Basquin and Paris laws would be helpful and have made changes to the text. These changes are primarily to the introduction section, where we directly address the application of the Basquin and Paris laws to our study; further discussion of Basquin's law and our results is in the discussion section.

The Brantut et al. (2013) review paper is really a paper about subcritical failure under *static* loading – and it does not describe cyclic loading or the classic Paris and Basquin laws at all. We include this reference in the introduction now, along with some text pointing out the relation between subcritical crack growth and fatigue failure, but also the difference that much of the rock mechanics literature focuses on static loading while fatigue failure is all about cyclic stresses.

• For this subcritical to critical regime, as the impact strength approaches the tensile strength (fracture toughness) of the rock, the probability of fragmentation due to crack propagation would exponentially increase (after empirical relationships like Paris' Law). It seems this theory could also be called on to explain your observations.

Paris' law and Basquin's law are related; the classical Basquin's law describes the lifetime of a particle in terms of collision cycles, while Paris' law describes the rate of propagation of a crack per cycle. In principle, the later is the derivative of the former.

The issue is that there's not a complete theory to support which kind of functional form (for Paris' or Basquin's law) should be exhibited. The Pal et al. (2021) result is a direct numerical simulation that produces a power-law function for Basquin's law; this result is certainly consistent with the more crude observations from past experiments, and with the "laws" mentioned above. We have added statements about the similarity of Basquin and Paris laws to the introduction section, and the reference below:

- Pugno, N., Ciavarella, M., Cornetti, P., and Carpinteri, A.: A generalized Paris' law for fatigue crack growth, *Journal of the Mechanics and Physics of Solids*, 54, 1333–1349, 2006.

• Ok – I see that you get to this in the discussion, but it seems a bit buried – and focused on 'life time' rather than 'cracking velocity'. Why not acknowledge this conceptual framework up front?
See the points above. It seems that this has mostly to do with which "law" – Basquin or Paris – one is familiar with. In our experiments we cannot measure crack velocity, but we can (and do) measure lifetime of a particle. This is why, for the experiments, connecting to Basquin's law makes sense. However, as mentioned earlier, we now point the reader to the connection between the two laws. As suggested, we have streamlined text and moved some of the discussion material to the introduction.
It seems a simpler conceptual model for what you observe than what is presented. You even acknowledge that is likely what is happening.
We are not sure that we understand this statement.
Also it would represent some of the first acknowledgement of the role of subcritical cracking generally in bedload attrition – which would eventually bring in the roll of climate, water temperature and chemistry etc.
Yes; but with the caveat that chipping is NOT subcritical cracking in the traditional sense because a system-spanning crack will never occur. This is the biggest distinction; the reviewer anticipated the fatigue failure regime – which is related to the 'cleavage' regime in the Pal et al. (2021) simulations – but the chipping regime is not something addressed in the fatigue failure literature. We have made an effort to clear this up by discussing the distinction in the introduction section.

• At a minimum it should be acknowledged that fatigue growth of cracking is a subcritical mechanism of time-dependent failure (see Atkinson, 1987) that is marked by progressive lengthening of individual cracks; and that such subcritical growth of fractures causes material strength to decrease. And that fragmentation is 'critical failure' by rapid unstable growth of an entire fracture network. This is an unambiguous unequivocal rock mechanics concept to point out that nicely explains your data.
We do not disagree. Indeed, this is basically what we have said and argued. The primary difference is that this concept has arisen several times in several different fields and described

in several different ways. In the revised manuscript we have now made the connections to classic rock mechanics more explicit, while also acknowledging the 'continuous phase transition' concept derived and suggested from materials science and physics.

• The resulting comparisons between 'strong' vs. 'weak' appear to support a subcritical progressive linear phase of cracking well below the material strength Fig 6), that is insensitive to material strength (consistent with fractures growing subcritically at impact energies well below the strength; controlled instead by subcritical material parameters).
But as far as we can tell, subcritical implies that eventually – with sufficient collisions – a large fracture can and will occur. The Pal et al. (2021) simulations and our experiments suggest something different; that there exists a regime where only compressional chipping cracks occur, which are parallel to the surface and therefore do not propagate into the bulk and eventually break the particle. As mentioned above, this distinction is stated in the text.

• In any context, what, then, is chipping? Critical Fragmentation at a much smaller length scale? That is the real question here that your data can't really address, as you say, because of your high variance in strength. Very interesting.
See the points above. We do agree that we would like more data. But the agreement of our current data with the Pal et al. (2021) simulations encourages us to support their conclusion – that chipping is a different regime, related to compressional and surface-parallel cracking. This is the part that rock mechanics hasn't addressed so much, but other mechanics of materials studies (like Ghadiri and Zhang (2002) or Pal et al. (2021)) have.

2) Organization & clarity.

Similar to the other reviews, I still find the introduction to still be a bit overly long and wordy. I don't finish reading it fully understanding – from what is written there – why we should care to know that there is a continuous phase transition. It feels buried.
See points above. The introduction section has been streamlined. We have moved aspects of the discussion related to Basquin's law to the introduction; and we have discussed the relation of Basquin and Paris laws, and how they connect to the continuous phase transition framework of Ghadiri and Zhang (2002) and Pal et al. (2021). We have also added emphasis on the importance of studying the transition from chipping to fragmentation (i.e., why our study matters).

In pg 14 line 2. "proposed that in the low energy limit of impact attrition, the number of impacts required to cause dynamic fragmentation, Ni, diverges" Diverges from what to what? Meaning not clear.
Text has been edited, and the paragraph containing this has been deleted.

Section 3.1– is this really how you want to lead off your results?! With a long discussion of why your cement did not behave? This entire section can be moved to the end of the results, and the 'whys' to the discussion as a caveat to your interpretation.

Agreed that this is not a strong way to begin the results section. The discussion of our concrete not behaving has been moved to the end of the material strength results section, as appropriate.

Indeed, the results section does not seem to clearly make the link between the stated goal of the proposed study and the results from the methods used. This could be addressed by some clear statements at the beginning of the methods – we measure xxx in order to determine xxxx. If we see xxx in our results, then we can interpret that as pxxx. The sentence along these lines"By measuring attrition rate, particle shape, and material strength under a known collision energy, we are able to characterize the relevant quantities needed to examine the transition from chipping to fragmentation." at the end of the introduction is sufficiently vague as to provide no clarity or direct link for the reader.
The methods section has been modified; the text is broken into several sub-sections that more directly relate each step of the methods to what we find out in the results.

Another example of this is the first line of the conclusion – where you talk about particle shape. The reader should have a clear sense from the beginning how and why this maters, but does not.
The conclusion section has been edited and no longer features this line. The new sentence that begins the conclusion directly states the purpose of the study.

Overall, the manuscript seems quite rambly and poorly focused. There are real gems of conclusion and results in there, but the reader has to work to find them.
Hopefully, the reader will find the manuscript to be clearer and more focused following these revisions. See previous responses regarding changes to improve readability and focus.

1) Other minor points/questions
Folks cite 10-20% of strength for a subcritical threshold. Do you see that in your data?
We are not sure that we understand this statement and cannot address if this is present in our data. The results section does address the observed material strength threshold at which chipping shifts to fatigue failure/fragmentation.

What controversy is there over fracture toughness? In fact it is very relevant because how it changes as cracks grow for a given impact energy directly speaks to the existing flaws in the material being fractured, and again provides a nice conceptual framework that is consistent with your observations.
Discussion on fracture toughness was removed, for clarity and brevity.

Why does material strength change – because cracks are growing. I don't see this link drawn clearly as an explanation of the overall gradation between chipping to fragmentation.
We are unsure what the reviewer means by this statement; however, we discuss both the mechanistic differences between chipping and fragmentation, and our observations regarding the transition from one attrition mechanism to the other.

The newly incorporated discussion of results by Pal et al., (2021) strenghthens the overall conclusions/results of the study.
We are glad that the Reviewer agrees that the findings of Pal et al. (2021) strengthen our study.

BRANTUT, N., HEAP, M., MEREDITH, P. & BAUD, P. 2013. Time-dependent cracking and brittle creep in crustal rocks: A review. Journal of Structural Geology, 52, 17-43.
We have added other references thanks to the Reviewer; but this one doesn't cover the fatigue failure "laws" for cyclic stress, so we thought it is best to leave out at the suggested location (discussion section). However, we have included it now in the introduction.

The other reference we added are mostly related to classic rock mechanics work on subcritical cracking, but some are also from the mechanics and physics literature. Here is a the list of references added:

- Pugno, N., Ciavarella, M., Cornetti, P., and Carpinteri, A.: A generalized Paris' law for fatigue crack growth, *Journal of the Mechanics and Physics of Solids*, 54, 1333–1349, 2006.
- Atkinson, B. K.: Subcritical crack growth in geological materials, *Journal of Geophysical Research: Solid Earth*, 89, 4077–4114, 1984.
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- Kun, F., Carmona, H., Andrade Jr, J. S., and Herrmann, H. J.: Universality behind Basquin's law of fatigue, *Physical review letters*, 100,094 301, 2008.
- Kim, H. S.: Prediction of SN curves at various stress ratios for structural materials, *Procedia Structural Integrity*, 19, 472–481, 2019.
- Verdian, J. P., Sklar, L. S., Riebe, C. S., and Moore, J. R.: Sediment size on talus slopes correlates with fracture spacing on bedrock cliffs: Implications for predicting initial sediment size distributions on hillslopes, *Earth Surface Dynamics*, 9, 1073–1090, 2021.